

# FIBER-RING OPTICAL RESONATORS

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## RELATED APPLICATIONS

This application claims benefit of prior filed co-pending provisional Application No. 60/183,499 entitled "Resonant optical power control devices and methods of fabrication thereof" filed 02/17/2000 in the names of Peter C. Sercel and Kerry J. Vahala, said provisional application being hereby incorporated by reference as if fully set forth herein. This application claims benefit of prior filed co-pending provisional Application No. 60/226,147 entitled "Fiber-optic waveguides for evanescent optical coupling and methods of fabrication and use thereof", filed 08/18/2000 in the names of Peter C. Sercel, Guido Hunziker, and Robert B. Lee, said provisional application being hereby incorporated by reference as if fully set forth herein.

## GOVERNMENT RIGHTS

The U.S. Government may have limited rights in this application pursuant to Office of Naval Research Contract No. N00014-00-1-0072 via California Institute of Technology Subcontract No. 1008921.

## FIELD OF THE INVENTION

The field of the present invention relates to optical fiber communications. In particular, novel optical components, and methods of fabrication and use thereof, are described herein for modulating, switching, routing, and otherwise controlling optical signals in a wavelength specific manner.

## BACKGROUND

This application is related to subject matter disclosed in: A1) U.S. provisional Application No. 60/111,484 entitled "An all-fiber-optic modulator" filed 12/07/1998 in the names of Kerry J. Vahala and Amnon Yariv, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein;

- 1 A2) U.S. Application No. 09/454,719 entitled "Resonant optical wave power control devices  
2 and methods" filed 12/07/1999 in the names of Kerry J. Vahala and Amnon Yariv, said  
3 application being hereby incorporated by reference in its entirety as if fully set forth  
4 herein;
- 5 A3) U.S. provisional Application No. 60/108,358 entitled "Dual tapered fiber-microsphere  
6 coupler" filed 11/13/1998 in the names of Kerry J. Vahala and Ming Cai, said provisional  
7 application being hereby incorporated by reference in its entirety as if fully set forth  
8 herein;
- 9 A4) U.S. Application No. 09/440,311 entitled "Resonator fiber bi-directional coupler" filed  
10 11/12/1999 in the names of Kerry J. Vahala, Ming Cai, and Guido Hunziker, said  
11 application being hereby incorporated by reference in its entirety as if fully set forth  
12 herein; and
- 13 A5) U.S. provisional Application No. 60/183,499 entitled "Resonant optical power control  
14 devices and methods of fabrication thereof" filed 02/17/2000 in the names of Peter C.  
15 Sercel and Kerry J. Vahala, said provisional application being hereby incorporated by  
16 reference in its entirety as if fully set forth herein.
- 17 A6) U.S. provisional application entitled "Fiber-optic waveguides for evanescent optical  
18 coupling and methods of fabrication and use thereof", filed 08/18/2000 in the names of  
19 Peter C. Sercel, Guido Hunziker, and Robert B. Lee, Application No. 60/226,147, said  
20 provisional application being hereby incorporated by reference in its entirety as if fully  
21 set forth herein.
- 22 A7) U.S. provisional Application No. 60/257,248 entitled "Modulators for resonant optical  
23 power control devices and methods of fabrication and use thereof" filed 12/21/2000 in  
24 the names of Oskar J. Painter, Peter C. Sercel, Kerry J. Vahala, and Guido Hunziker, said  
25 provisional application being hereby incorporated by reference as if fully set forth herein.
- 26 A8) U.S. provisional application entitled "Waveguides and resonators for integrated optical  
27 devices and methods of fabrication and use thereof", filed 12/21/2000 in the name of  
28 Oskar J. Painter, Application No. 60/257,218, said provisional application being hereby  
29 incorporated by reference as if fully set forth herein.

- 1 A9). U.S. utility patent Application No. \_\_\_\_/\_\_\_\_,\_\_\_\_ (not yet assigned; Docket No.  
2 ALG06NP) entitled "Cylindrical processing of a optical media" filed concurrently with  
3 the present application in the names of Peter C. Sercel, Kerry J. Vahala, David W.  
4 Vernoooy, and Guido Hunziker, said application being hereby incorporated by reference  
5 as if fully set forth herein.
- 6 A10). U.S. utility patent Application No. \_\_\_\_/\_\_\_\_,\_\_\_\_ (not yet assigned; Docket No.  
7 ALG07NP) entitled "Fiber-ring optical resonators" filed concurrently with the present  
8 application in the names of Peter C. Sercel, Kerry J. Vahala, David W. Vernoooy, Guido  
9 Hunziker, and Robert B. Lee, said application being hereby incorporated by reference as  
10 if fully set forth herein.
- 11 A11). U.S. utility patent Application No. \_\_\_\_/\_\_\_\_,\_\_\_\_ (not yet assigned; Docket No.  
12 ALG08NP) entitled "Resonant optical filter" filed concurrently with the present  
13 application in the names of Kerry J. Vahala, Peter C. Sercel, David W. Vernoooy, Oskar J.  
14 Painter, and Guido Hunziker, said application being hereby incorporated by reference as  
15 if fully set forth herein.
- 16 A12). U.S. utility patent Application No. \_\_\_\_/\_\_\_\_,\_\_\_\_ (not yet assigned; Docket No.  
17 ALG10NP) entitled "Resonant optical power control device assemblies" filed  
18 concurrently with the present application in the names of Peter C. Sercel, Kerry J.  
19 Vahala, David W. Vernoooy, Guido Hunziker, Robert B. Lee, and Oskar J. Painter, said  
20 application being hereby incorporated by reference as if fully set forth herein.
- 21 A13) U.S. provisional Application No. 60/170,074 entitled "Optical routing/switching based on  
22 control of waveguide-ring resonator coupling", filed 12/09/1999 in the name of Amnon  
23 Yariv, said provisional application being hereby incorporated by reference in its entirety  
24 as if fully set forth herein.
- 25 A14) U. S. Pat. No. 6,052,495 entitled "Resonator modulators and wavelength routing  
26 switches" issued 04/18/2000 in the names of Brent E. Little, James S. Foresi, and  
27 Hermann A. Haus, said patent being hereby incorporated by reference in its entirety as if  
28 fully set forth herein.

A15) U. S. Pat. No. 6,101,300 entitled “High efficiency channel drop filter with absorption induced on/off switching and modulation” issued 08/08/2000 in the names of Shanhui Fan, Pierre R. Villeneuve, John D. Joannopoulos, Brent E. Little, and Hermann A. Haus, said patent being hereby incorporated by reference in its entirety as if fully set forth herein.

This application is also related to subject matter disclosed in the following 17 publications, each of said 17 publications being hereby incorporated by reference in its entirety as if fully set forth herein:

P1) Ming Cai, Guido Hunziker, and Kerry Vahala, “Fiber-optic add-drop device based on a silica microsphere whispering gallery mode system”, IEEE Photonics Technology Letters Vol. 11 686 (1999);

P2) J. C. Knight, G. Cheung, F. Jacques, and T. A. Birks, “Phased-matched excitation of whispering gallery-mode resonances by a fiber taper”, Optics Letters Vol. 22 1129 (1997);

P3) Hiroshi Wada, Takeshi Kamijoh, and Yoh Ogawa, “ Direct bonding of InP to different materials for optical devices”, Proceedings of the third international symposium on semiconductor wafer bonding: Physics and applications, Electrochemical Society Proceedings, Princeton NJ, Vol. 95-7, 579 –591 (1995).

P4) R. H. Horng, D. S. Wu, S.C. Wei, M. F. Huang, K.H. Chang, P.H. Liu, and K. C. Lin, “AlGaInP/AuBe/glass light emitting diodes fabricated by wafer-bonding technology”, Appl. Phys. Letts. Vol. 75(2) 154 (1999).

P5) Y. Shi, C. Zheng, H. Zhang, J.H. Bechtel, L.R. Dalton, B.B. Robinson, W. Steier, “Low (sub-1-volt) halfwave voltage polymeric electro-optic modulators achieved by controlling chromophore shape”, Science Vol. 288, 119 (2000).

P6) E. L. Wooten, K.M. Kissa, and A. Yi-Yan, “A review of lithium niobate modulators for fiber-optic communications systems”, IEEE J. Selected Topics in Quantum Electronics, Vol. 6(1), 69 (2000).

P7) D.L. Huffaker, H. Deng, Q. Deng, and D.G. Deppe, “Ring and stripe oxide-confined vertical-cavity surface-emitting lasers”, Appl. Phys. Lett., Vol. 69(23), 3477 (1996).

- 1 P8) Serpenguzel, S. Arnold, and G. Griffel, "Excitation of resonances of microspheres on an  
2 optical fiber", *Opt. Lett.* Vol. 20, 654 (1995);
- 3 P9) F. Treussart, N. Dubreil, J. C. Knight, V. Sandoghar, J. Hare, V. Lefevre-Seguin, J. M.  
4 Raimond, and S. Haroche, "Microlasers based on silica microspheres", *Ann.*  
5 *Telecommun.* Vol. 52, 557 (1997); and
- 6 P10) M. L. Gorodetsky, A. A. Savchenkov, V. S. Ilchenko, "Ultimate Q of optical microsphere  
7 resonators", *Optics Letters*, Vol. 21, 453 (1996).
- 8 P11) Ming Cai, Oskar Painter, and Kerry J. Vahala, "Observation of critical coupling in a fiber  
9 taper to a silica-microsphere whispering-gallery mode system", *Physical Review Letters*,  
10 Vol. 85(1) 74 (2000).
- 11 P12) Andreas Othonos, "Fiber Bragg gratings", *Rev. Sci. Instrum.* Vol. 68(12) 4309 (1997).
- 12 P13) B.A. Little, S.T. Chu, H. A. Haus, J. Foresi, and J.-P. Laine, "Microring channel dropping  
13 filters", *J. Lightwave Technology* Vol. 15 998 (1997).
- 14 P14) Giora Griffel, "Synthesis of optical filters using ring resonator arrays", *IEEE Photonics*  
15 *Technology Letts.* Vol. 12 810 (2000).
- 16 P15) G. Metz et al., « Bragg grating formation and germanosilicate fiber photosensitivity",  
17 *SPPIE Vol 1516 Int. Workshop on Photoinduced Self-organization in Optical Fiber*  
18 (1991).
- 19 P16) T. Erdogan, V. Mizrahi, P. J. Lemaire, and D. Monroe, "Decay of UV-induced fiber  
20 Bragg gratings", *J. Appl. Phys.* Vol. 76 73 (1994).
- 21 P17) Wei Xu, Mank Janos, Danny Wong, Simon Fleming, "Thermal poling of boron-codoped  
22 germanosilicate", *IEICE Trans. Electron.*, Vol E82-C(8) 1549 (1999).

23 Optical fiber and propagation of high-data-rate optical pulse trains therethrough has  
24 become the technology of choice for high speed telecommunications. Wavelength division  
25 multiplexing (WDM) techniques are now commonly used to independently transmit a plurality  
26 of signals over a single optical fiber, independent data streams being carried by optical fields  
27 propagating through the optical fiber at a slightly differing optical carrier wavelengths (i.e.,  
28 signal channels). WDM techniques include dense wavelength division multiplexing (DWDM)  
29 schemes, wherein the frequency spacing between adjacent signal channels may range from a few

1 hundred GHz down to a few GHz. A propagating mode of a particular wavelength must be  
2 modulated, independently of other propagating wavelengths, in order to carry a signal. A signal  
3 carried by a particular wavelength channel must be independently accessible for routing from a  
4 particular source to a particular destination. These requirements have previously required  
5 complex and difficult-to-manufacture modulating and switching devices requiring extensive  
6 active alignment procedures during fabrication/assembly, and as a result are quite expensive.  
7 Such devices may require conversion of the optical signals to electronic signals and/or vice  
8 versa, which is quite power consuming and inefficient. In the patent applications A1 through  
9 A14 cited above a new approach has been disclosed for controlling optical power transmitted  
10 through an optical fiber that relies on the use of resonant circumferential-mode optical  
11 resonators, or other optical resonators, for direct optical coupling to a propagating mode of an  
12 optical fiber resonant with the optical resonator, thereby enabling wavelength-specific  
13 modulation, switching, and routing of optical signals propagating through the optical fiber. A  
14 thorough discussion of the features and advantages of such optical power control devices and  
15 techniques, as well as methods of fabrication, may be found in these applications, already  
16 incorporated by reference herein.

17 One important element of these latter devices is optical coupling between a fiber-optic  
18 waveguide and a circumferential-mode optical resonator. The circumferential-mode optical  
19 resonator provides wavelength specificity, since only propagating optical modes substantially  
20 resonant with the circumferential-mode optical resonator will be significantly affected by the  
21 device. A fiber-optic waveguide for transmitting the optical signal through the control device is  
22 typically provided with an evanescent optical coupling segment, where an evanescent portion of  
23 the propagating optical mode extends beyond the waveguide and overlaps a portion of a  
24 circumferential optical mode of the circumferential-mode optical resonator, thereby optically  
25 coupling the circumferential-mode optical resonator and the fiber-optic waveguide. The  
26 evanescent optical coupling segment may take one of several forms, including an optical fiber  
27 taper, D-shaped optical fiber, an optical fiber with a saddle-shaped concavity in the cladding  
28 layer, and/or other functionally equivalent configurations. These are discussed in detail in patent  
29 applications A1 through A7 cited herein.

30 The circumferential-mode optical resonator structure may comprise a glass micro-sphere  
31 or micro-disk, a fiber-ring resonator, a semiconductor ring/waveguide, or other functionally

1 equivalent structure, described in detail in earlier-cited applications A1 through A8. A high-Q  
2 circumferential-mode optical resonator supports relatively narrow-linewidth resonant  
3 circumferential optical modes (i.e., having a linewidth consistent with typical linewidths of a  
4 WDM system, TDM system, or other optical data transmission system), which in an optical  
5 power control device may optically couple to propagating optical modes of the fiber-optic  
6 waveguide of substantially resonant optical wavelength. The circumferential-mode optical  
7 resonator therefore provides the wavelength selectivity of the optical power control device.  
8 Non-resonant propagating optical signals pass by the circumferential-mode optical resonator  
9 relatively undisturbed, and are transmitted through the device. The effect of the device on a  
10 substantially resonant signal channels depends on the nature of the control device.

11 A resonant optical filter may be constructed by coupling a second optical waveguide to  
12 the resonator to a similar degree that the fiber-optic waveguide is optically coupled to the  
13 resonator. In this case a critical-coupling condition exists between the resonator and fiber-optic  
14 waveguide, and for this condition substantially all of the resonant optical signal will be  
15 transferred from the fiber-optic waveguide to the second waveguide. Such a configuration is  
16 useful for constructing channel slicer/interleavers or channel add/drop filters for WDM and/or  
17 WDM optical transmission systems. Such a device enables wavelength-specific routing of one  
18 or more resonant signal channels among group of signal channels.

19 Alternatively, a resonant optical modulator or switch may be constructed by providing  
20 the circumferential-mode optical resonator with an optical loss mechanism that may be actively  
21 controlled or modulated. By modulating the resonator loss between critical-coupling and either  
22 over- or under-coupling, the transmission of a resonant signal channel may be selectively  
23 modulated between near-zero transmission and non-zero transmission. Since the circumferential-  
24 mode optical resonator provides wavelength(i.e., signal channel) specificity, the optical loss  
25 mechanism need not be wavelength specific.

26 It is therefore desirable to provide resonant optical power control devices for providing  
27 wavelength specific modulation of an optical signal channel. It is therefore desirable to provide  
28 resonant optical power control devices for providing wavelength specific routing of an optical  
29 signal channel. It is desirable to provide fiber-ring resonators for incorporation into resonant  
30 optical power control devices as the circumferential mode optical resonator. It is therefore

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[illegible]



## SUMMARY

Certain aspects of the present invention may overcome one or more aforementioned drawbacks of the previous art and/or advance the state-of-the-art of optical power control devices and fabrication thereof, and in addition may meet one or more of the following objects:

To provide cylindrical processing methods and apparatus for processing optical media;

To provide cylindrical processing methods and apparatus wherein rings and partial rings may be machined onto an optical fiber;

To provide cylindrical processing methods and apparatus for producing a fiber-ring optical resonator;

To provide delocalized-optical-mode suppressors for substantially eliminating undesirable optical resonance of the fiber-ring and/or optical fiber;

To provide cylindrical processing methods and apparatus for producing fiber-taper positioner on an optical fiber;

To provide a resonant optical power control device that may be reliably and reproducibly fabricated;

To provide a resonant optical power control device that may be reliably and reproducibly fabricated without resorting to active alignment procedures;

To provide a resonant optical power control device with low insertion loss;

To provide a resonant optical power control device with a free spectral range suitable for use in WDM applications;

To provide a resonant optical power control device wherein an optical wave propagating through an optical fiber is coupled to a resonant circumferential-mode optical resonator;

To provide a method for fabricating a circumferential-mode optical resonator on the circumference of an optical fiber, thereby providing a fiber-ring resonator;

1 To provide a method for fabricating a circumferential-mode optical resonator on  
2 the circumference of an optical fiber by altering a circumferential optical pathlength (by  
3 altering diameter, refractive index, chemical composition, density, and so on) of a  
4 transverse resonator segment of the optical fiber;

5 To provide a method for fabricating an optical power control device wherein the  
6 optical fiber and the circumferential-mode resonator are positioned and secured within  
7 alignment grooves on an alignment substrate;

8 To provide a method for fabricating an optical power control device wherein the  
9 circumferential-mode resonator is provided with an alignment groove and/or flange for  
10 passive alignment within an alignment grooves on an alignment substrate;

11 To provide a method for fabricating an optical power control device wherein the  
12 optical fiber has a fiber taper segment for optically coupling to the circumferential-mode  
13 resonator;

14 To provide a method for fabricating an optical power control device wherein the  
15 optical fiber may be heated and pulled to form a fiber taper segment within an alignment  
16 groove on an alignment substrate; and

17 To provide a method for fabricating an optical power control device wherein a  
18 fiber taper segment may be received by a fiber-taper positioner provided on or near the  
19 circumferential-mode optical resonator;

20 To provide a method for fabricating an optical power control device wherein a  
21 fiber taper segment may be wrapped around a circumferential-mode optical resonator;

22 To provide a method for fabricating a resonant optical filter by providing a second  
23 fiber-optic waveguide coupled to the circumferential-mode optical resonator; and

24 To provide a method for fabricating a resonant optical modulator by providing a  
25 modulator for controlling optical properties of the circumferential-mode resonator.

26 One or more of the foregoing objects may be achieved in the present invention by a  
27 method for fabricating a circumferential-mode optical resonator on an optical fiber, comprising  
28 the step of generating a differential of a circumferential optical pathlength (by altering diameter,

density, refractive index, chemical composition, and so forth) of a transverse resonator fiber segment relative to the longitudinally adjacent fiber segments. The resonator fiber segment may therefore substantially confine a circumferential optical mode propagating around the resonator fiber segment circumference at least partially within the resonator fiber segment. Specialized techniques for spatially selectively generating the differential may include masking/etching, masking/deposition, laser machining, laser patterning, combinations thereof, and/or functional equivalents thereof. The circumferential-mode resonator may be further provided with an alignment flange and/or groove for enabling passive positioning of the circumferential-mode resonator within an alignment groove of an alignment substrate. A preferred method for fabricating an optical power control device according to the present invention comprises the steps of: 1) fabricating a circumferential-mode resonator as described herein; 2) heating and pulling a transmission optical fiber to form a fiber taper segment; 3) fabricating an alignment substrate having a resonator-alignment groove and a fiber alignment groove thereon; 4) positioning and securing the fiber taper segment within the fiber-alignment groove; 5) positioning and securing the circumferential-mode resonator within the resonator-alignment groove so that the circumferential-mode resonator and the fiber taper segment are optically coupled (through close proximity and/or direct contact between them). The alignment grooves are fabricated at the correct depths and positions and with corresponding alignment grooves and/or flanges to enable the optical coupling without extensive active alignment procedures. Additional alignment structures and positioners may be provided to facilitate and adjust optical coupling of the circumferential-mode resonator and the fiber-optic taper. In a resonant optical filter, a second fiber-optic taper may be coupled to the resonator. In a resonant optical modulator, a modulator may be provided as an integral component of the circumferential-mode resonator, provided directly on the circumferential-mode resonator, or as a separate assembly positioned on and secured with respect to the alignment substrate. The modulator enables control of the optical properties of the circumferential-mode resonator, which in turn enables control of the optical power transmitted through the fiber taper segment of the transmission optical fiber.

Additional objects and advantages of the present invention may become apparent upon referring to the preferred and alternative embodiments of the present invention as illustrated in the drawings and described in the following written description and/or claims.

## BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1A and 1B show side and transverse cross-sectional views, respectively, of a circumferential-mode optical resonator fabricated on an optical fiber according to the present invention.

Figures 2A, 2B, and 2C show schematically intensity profiles for the three lowest order transverse circumferential modes of a circumferential-mode optical resonator on an optical fiber according to the present invention.

Figure 3 illustrates a method for fabricating a circumferential-mode resonator on an optical fiber according to the present invention. All views are side views, and stippled shading indicates the presence of an outer coating on the outer surface of the optical fiber.

Figure 4 shows schematically an apparatus for highly concentric rotation of an optical fiber during laser machining or other fabrication process according to the present invention.

Figure 5 shows an optical fiber being laser-machined according to the present invention.

Figure 6 shows reduction of the diameter of a circumferential-mode resonator on an optical fiber according to the present invention.

Figure 7 illustrates a method for fabricating a circumferential-mode resonator on an optical fiber according to the present invention. All views are side cross-sectional views.

Figure 8A illustrates a method for fabricating a circumferential-mode resonator on an optical fiber according to the present invention. All views are side cross-sectional views, and the density of the stippled shading indicates the relative refractive index, density, and/or dopant concentration.

Figures 8B and 8C show reduction of the diameter of a circumferential-mode resonator on an optical fiber according to the present invention.

Figures 9A and 9B show a WGM resonator on an optical fiber with alignment and/or indexing structures provided thereon according to the present invention.

Fig. 10 shows a fiber-ring resonator with optical mode suppressors.

Figs. 11A, 11B, and 11C are two partial sectional views and one top view, respectively, of an optical power control device according to the present invention.

1 Figs. 12A and 12B are partial sectional views of an optical power control device  
2 according to the present invention.

3 Figs. 13A and 13B are partial sectional views of an optical power control device  
4 according to the present invention.

5 Figs. 14A and 14B are partial sectional views of an optical power control device  
6 according to the present invention.

7 Figure 15 is a cross-sectional views (looking along a resonator-alignment groove) of an  
8 optical power control device according to the present invention.

9 Figure 16 is a top view of a circumferential-mode resonator on an optical fiber having  
10 alignment structures thereon that are engaged with corresponding alignment structures in  
11 resonator-alignment groove according to the present invention.

12 Figure 17 illustrates a method for assembling an optical power control device on an  
13 alignment substrate according to the present invention.

14 Figure 18 is a cross-sectional views (looking along a resonator-alignment groove) of an  
15 optical power control device according to the present invention.

16 Figure 19 is a cross-sectional views (looking along a resonator-alignment groove) of an  
17 optical power control device according to the present invention.

18 Figure 20 is a top view of an optical power control device according to the present  
19 invention.

20 Figure 21 is a cross-sectional views (looking along a resonator-alignment groove) of an  
21 optical power control device according to the present invention.

22 Figure 22 shows the spectral properties of a coupled optical resonator system.

23 It should be noted that the relative proportions of various structures shown in the Figures  
24 may be distorted to more clearly illustrate the present invention. In particular, the size  
25 differential and resonator thickness of fiber-rings may be greatly exaggerated relative to the  
26 underlying optical fiber diameter in various Figures for clarity. Various metal, semiconductor,  
27 and/or other thin films, layers, and/or coatings may also be shown having disproportionate and/or  
28 exaggerated thicknesses for clarity. Relative dimensions of various waveguides, resonators,  
29 optical fibers/tapers, and so forth may also be distorted, both relative to each other as well as

1 transverse/longitudinal proportions. For example, several Figures showing a lateral view of a  
2 fiber-taper show the length of fiber over which the taper occurs much shorter than is actually the  
3 case. The text and incorporated references should be relied on for the appropriate dimensions  
4 and/or proportions of structures shown herein.

5 It should be noted that some of the Figures may each may depict one of several distinct  
6 embodiments of optical power control devices according to the present invention. Each set of  
7 embodiments corresponding to a particular Figure are similar in spatial arrangement, but differ in  
8 functional details that are not represented in the Figures. In particular, loss-modulated, index-  
9 modulated, resonance-modulated, interference-modulated embodiments may appear substantially  
10 similar in the Figures. The particular functional aspects of the different embodiments are  
11 described in different text sections that each refer to one or more common Figures.

## DETAILED DESCRIPTION OF PREFERRED AND ALTERNATIVE EMBODIMENTS

For purposes of the present written description and/or claims, “circumferential-mode optical resonator” (equivalently, CMOR, CM optical resonator, CM resonator, CMR) shall denote a resonator structure capable of supporting a substantially resonant circumferential optical mode (equivalently, RCOM), the circumferential optical mode having an evanescent portion extending beyond the circumferential-mode optical resonator and typically being substantially confined near the surface of the resonator (near being defined here as within several microns for visible, near-, or mid-infrared circumferential optical modes). Such a resonator has been/is also often referred to as a whispering-gallery-mode optical resonator (near in this case). Such resonator structures may include, but are not limited to, spheres, near-spheres, oblate and/or prolate spheroids, ellipsoids, ovals, ovoids, racetracks, polygons, polyhedra, cylinders, disks, rings, micro-spheres, micro-disks, micro-rings, fiber-rings, disks and/or rings on substrates (including structures disclosed in earlier-cited application A8), ring or other closed waveguides, and/or functional equivalents thereof. In particular, the various circumferential-mode optical resonator structures as disclosed in earlier-cited application A5 (denoted collectively as “fiber-rings”, fiber-ring resonator, or FRR’s) are particularly noted for inclusion as circumferential-mode optical resonators for purposes of this disclosure. However, other resonator structures may be equivalently employed without departing from inventive concepts disclosed and/or claimed herein. Any resonator having an evanescent portion of a resonant optical mode or that may otherwise be “evanescently optically coupled” to another optical element (see definition hereinbelow) may be employed as the resonant optical resonator element of the present invention (i.e., the element that confers wavelength specificity on the optical power control device). Optical resonator structures disclosed in earlier-cited application A8 (denoted collectively as “DBR rings”) are particularly noted for inclusion as optical resonators suitable for use in the present invention. Although the term “circumferential-mode optical resonator” is used throughout the remainder of the present disclosure, it should be understood that any optical resonator that may be evanescently optically coupled to a transmission waveguide and/or to an optical modulator as disclosed herein shall be considered functionally equivalent to a circumferential-mode optical resonator.

1 It should also be noted that the terms “optical resonator”, “circumferential-mode optical  
2 resonator”, and so forth shall encompass both single optical resonators as well as coupled  
3 systems of multiple optical resonators, unless a single- or multiple-resonator device is  
4 specifically designated in the text.

5 For purposes of the present written description and/or claims, “transmission fiber-optic  
6 waveguide” (equivalently, transmission waveguide, transmission fiber-optic, transmission optical  
7 fiber, TFOWG, TWG) shall denote an optical fiber (polarization-maintaining or otherwise)  
8 provided with a evanescent optical coupling segment where an evanescent portion of a  
9 propagating optical mode may extend beyond the fiber-optic waveguide and overlap a portion of  
10 some other optical mode, thereby enabling evanescent optical coupling between the transmission  
11 optical waveguide and another optical element. Such a transmission optical waveguide may  
12 comprise an optical fiber taper, a D-shaped optical fiber, an optical fiber with a saddle-shaped  
13 concavity in the cladding layer, an optical fiber with a side-polished flattened portion, and/or  
14 functional equivalents. Such transmission optical waveguides are described in further detail in  
15 earlier-cited applications A1 through A6. Such transmission fiber-optic waveguides typically  
16 serve to facilitate insertion of optical power control devices according to the present invention  
17 into an optical power transmission system.

18 For purposes of the written description and/or claims, “evanescent optical coupling” shall  
19 generally denote those situations in which two optical elements, each capable of supporting a  
20 propagating and/or resonant optical mode and at least one having an evanescent portion  
21 extending beyond its respective optical element, are optically coupled by at least partial spatial  
22 overlap of the evanescent portion of one optical mode with at least a portion of the other optical  
23 mode. The amount, strength, level, or degree of optical power transfer from one optical element  
24 to the other through such evanescent optical coupling depends on the spatial extent of the overlap  
25 (both transverse and longitudinal), the spectral properties of the respective optical modes, and the  
26 relative spatial phase matching of the respective optical modes (also referred to as modal index  
27 matching). To transfer optical power most efficiently, the respective modal indices of the optical  
28 modes (equivalently, the respective modal propagation constants), each in its respective optical  
29 element, must be substantially equal. Mismatch between these modal indices decreases the  
30 amount of optical power transferred by evanescent coupling between the optical elements, since  
31 the coupled modes get further out of phase with each other as each propagates within its



respective optical element and the direction of the optical power transfer eventually reverses itself. The propagation distance over which the modes interact (i.e., the effective interaction length) and the degree of index matching (or mis-matching) together influence the overall flow of optical power between the coupled modes. Optical power transfer between the coupled modes oscillates with a characteristic amplitude and spatial period as the modes propagate, each in its respective optical element. Neglecting the effects of optical loss in the optical elements, an ideal system consisting of two coupled modes can be characterized by the following coupled system of equations:

$$\begin{aligned}\frac{\partial E_1}{\partial z} &= i\beta_1 E_1 + i\kappa E_2 \\ \frac{\partial E_2}{\partial z} &= i\beta_2 E_2 + i\kappa^* E_1\end{aligned}$$

Where the following definitions apply:

$E_{1,2}$  amplitudes of the coupled fields  
 $\beta_{1,2}$  propagation constants of the coupled fields  
 $\kappa$  coupling amplitude resulting from spatial overlap of the fields  
 $z$  propagation distance coordinate

For the purpose of illustration, assume that the coupling amplitude  $\kappa$  is constant over an interaction distance  $L$ . Then, an incident field of amplitude  $E_1$  that is spatially confined to the first optical element before interaction will couple to the other wave guide with a resultant field amplitude  $E_2(L)$  at  $z=L$  (where we define  $z=0$  as the start of the coupling region) given by the following expression,

$$\begin{aligned}\frac{|E_2(L)|^2}{|E_1(0)|^2} &= \frac{|\kappa|^2}{q^2} \sin^2(qL) \\ q^2 &= |\kappa|^2 + \frac{1}{4}\Delta\beta^2\end{aligned}$$

Consider the phase mismatch term ( $\Delta\beta=\beta_2-\beta_1$ ) and the interaction length in this expression. As is well known, a condition of phase mismatch between the two spatial modes causes an oscillatory power transfer to occur between the waveguides as the interaction length is

1 varied. The spatial period of this oscillation, a so-called "beat length", can be defined as the  
2 distance over which power cycles back and forth between the guides. Greater amounts of phase  
3 mismatch will reduce the beat length. Also note that the absolute magnitude of power transfer  
4 will diminish with increasing phase mismatch. Finally, it is apparent that increased amounts of  
5 interaction length will introduce an increased spectral selectivity to the power coupling.

6 By controlling the phase mismatch and/or transverse spatial overlap between optical  
7 modes, these characteristics may be exploited for controlling optical power transfer between  
8 optical elements. For example, by altering the phase mismatch, a device may be switched from a  
9 first condition, in which a certain fraction of optical power is transferred from a first optical  
10 mode in a first optical element to a second optical mode in a second optical element (phase  
11 mismatch set so that the effective interaction length is about half of the characteristic spatial  
12 period described above), to a second condition in which little or no optical power is transferred  
13 (phase mismatch set so that the effective interaction length is about equal to the characteristic  
14 spatial period). Further discussion of optical coupling may be found in Fundamentals of  
15 Photonics by B. E. A. Saleh and M. C. Teich (Wiley, New York, 1991), hereby incorporated by  
16 reference in its entirety as if fully set forth herein. Particular attention is called to Chapters 7 and  
17 18.

18 It should be noted that optical power control devices, their fabrication, and their use  
19 according to the present invention are intended primarily for modulating a propagating optical  
20 mode having a wavelength between about 0.8  $\mu\text{m}$  and about 1.7  $\mu\text{m}$  (the wavelength range  
21 typically utilized for fiber-optic telecommunications). However, these devices, methods of  
22 fabrication, and methods of use may be adapted for use at any desired wavelength while  
23 remaining within the scope of inventive concepts disclosed and/or claimed herein.

24 In preferred and alternative methods for fabricating a circumferential-mode optical  
25 resonator as disclosed herein, an optical fiber (hereinafter including substantially cylindrical  
26 optical media) serves as the starting material for fabricating a ring-type circumferential-mode  
27 resonator; this fiber shall be referred to herein as the resonator fiber. Use of a ring or disk  
28 circumferential-mode resonator substantially eliminates the problem of closely-spaced modes  
29 that typically characterize nearly spherical circumferential-mode resonators. Use of an optical  
30 fiber as the starting material insures that the resulting circumferential-mode resonator will be

1 substantially circular, and facilitates subsequent optical coupling to and/or phase matching with  
2 an optical fiber, and assembly/alignment of the circumferential-mode resonator as part of an  
3 optical power control device. The circumferential-mode resonator is fabricated by generating a  
4 differential of some physical property of the optical fiber between a transverse resonator segment  
5 of the optical fiber and the two longitudinally adjacent portions of the surrounding segments of  
6 the resonator optical fiber. The preferred property is a circumferential optical pathlength. The  
7 optical pathlength differential enables substantial confinement by the resonator segment of the  
8 resonator fiber of a substantially resonant circumferential-mode optical wave that propagates  
9 around the circumference of the fiber at least partially within the resonator segment. A portion  
10 of the circumferential-mode optical wave comprises an evanescent wave extending outside the  
11 resonator segment longitudinally and/or radially. The evanescent wave portion of the  
12 circumferential-mode optical wave enables optical coupling of the circumferential-mode optical  
13 resonator to other optical components and modification and/or control of the optical properties,  
14 behavior, and performance of the circumferential-mode optical resonator.

15 In a preferred method for fabricating the circumferential-mode resonator, the diameter is  
16 the property of the optical fiber for which a differential is generated, thereby yielding a longer  
17 circumferential optical pathlength for the resonator segment (Figs. 1A and 1B). Optical fibers  
18 are commonly available commercially having a diameter of about 125  $\mu\text{m}$  (higher refractive  
19 index core plus lower refractive index cladding, excluding any additional jacket material), and  
20 other diameters are available. For use in a resonant optical modulator according to the present  
21 invention, the finished circumferential-mode resonator may have a diameter ranging between  
22 about 10  $\mu\text{m}$  and a few millimeters, preferably between about 20  $\mu\text{m}$  and about 200  $\mu\text{m}$ , and  
23 most preferably between about 100  $\mu\text{m}$  and about 150  $\mu\text{m}$ . For use in a resonant optical filter  
24 according to the present invention, the finished circumferential-mode resonator may have a  
25 diameter ranging between about 10  $\mu\text{m}$  and a few millimeters, preferably between about 400  $\mu\text{m}$   
26 and about 1000  $\mu\text{m}$ , and most preferably between about 500  $\mu\text{m}$  and about 600  $\mu\text{m}$ . For use in  
27 a resonant optical modulator according to the present invention, the finished circumferential-  
28 mode resonator may have radius differential (radius greater than the adjacent portion of the  
29 surrounding segments of the resonator fiber) ranging between about 0.1  $\mu\text{m}$  and about 20  $\mu\text{m}$ ,  
30 preferably between about 0.5  $\mu\text{m}$  and about 1.5  $\mu\text{m}$ . For use in a resonant optical filter according  
31 to the present invention, the finished circumferential-mode resonator may have radius differential

1 between about 0.1  $\mu\text{m}$  and about 10  $\mu\text{m}$ , preferably between about 0.1 and about 2  $\mu\text{m}$ . These  
2 size differentials are generally sufficient to substantially confine a circumferential mode with  
3 minimum number of nodes along the fiber axis or in the radial direction at least partially within  
4 the resonator segment 100, while not confining higher-order modes as well (if at all). The  
5 thickness of the resonator segment 100 may range between about 1  $\mu\text{m}$  and about 10  $\mu\text{m}$ ,  
6 preferably between about 2  $\mu\text{m}$  and about 4  $\mu\text{m}$ . This width is sufficient to support a  
7 circumferential mode with minimum number of nodes along the fiber axis or in the radial  
8 direction, which may extend longitudinally beyond the resonator segment, while not supporting  
9 higher-order circumferential-mode spatial modes as well. In particular, it has been observed that  
10 a circumferential-mode resonator having a diameter of about 125  $\mu\text{m}$ , a size differential of 1-2  
11  $\mu\text{m}$ , and a resonator segment thickness of about 5  $\mu\text{m}$  may support a circumferential mode with  
12 minimum number of nodes along the fiber axis or in the radial direction, but also higher-spatial-  
13 order circumferential-mode modes having planar nodal surfaces perpendicular to the axis of the  
14 resonator segment (Figures 2A, 2B, and 2C). These higher-spatial-order modes are frequency  
15 shifted with respect to the lowest-order mode, thereby degrading the frequency selectivity (i.e.,  
16 decreased frequency spacing between modes) of the circumferential-mode resonator. This  
17 problem may be mitigated in several ways. In a first method, it has been observed that a smaller  
18 size differential between the resonator segment 100 and the adjacent portions 200 (between  
19 about 0.5  $\mu\text{m}$  and about 1.5  $\mu\text{m}$ ) confines the circumferential optical modes more weakly than a  
20 larger size differential. This effect becomes substantially more pronounced for higher-spatial-  
21 order modes, which extend further beyond the resonator segment than lower-order modes as  
22 shown in Figs. 2A through 2C. Sufficient reduction of the size differential results in substantial  
23 suppression of all higher-order modes. Alternatively, in a second method the thickness of the  
24 resonator segment may be reduced from about 5  $\mu\text{m}$  to about 1  $\mu\text{m}$  in order to remove higher  
25 order spatial modes. Alternatively, a larger resonator thickness (perhaps several 10's of microns)  
26 may be desirable for enabling optical coupling of multiple fibers to a single circumferential-  
27 mode resonator; or a plurality of resonators positioned on the same fiber sufficiently close  
28 together to enable optical coupling between them may be employed to provide a tailored  
29 frequency filter function for optically coupling multiple fibers.

30 A preferred method for reducing the size of the adjacent portions relative to the resonator  
31 segment comprises the steps of: 1) providing the resonator segment with a mask; 2) spatially-

1 selectively etching the adjacent portions, thereby reducing their diameters relative to the  
2 diameter of the resonator segment; and 3) removing the mask (Fig. 3). Many optical fibers are  
3 supplied with an outer coating comprising a polymer jacket (acrylate, polyimide, or the like), and  
4 this jacket may be used as a mask provided it adheres sufficiently to the optical fiber during  
5 etching. A preferred mask may comprise an outer fiber coating (shown as stippled shading in  
6 Fig. 3) comprising a carbon coating. Optical fiber having a hermetic carbon outer coating (with  
7 or without a polymer jacket over the hermetic carbon coating) may be obtained commercially  
8 (Hermeticoat optical fiber, sold by Spectran Specialty Optics) or may be fabricated by deposition  
9 of a carbon layer on the fiber cladding (see for example U.S. Patent No. 5,281,247, said patent  
10 being hereby incorporated by reference in its entirety as if fully set forth herein). A carbon  
11 coating has been found to adhere very well to the optical fiber during etching of the optical fiber.  
12 A metal coating may also be employed, and whatever type of coating is used, it may first be  
13 deposited on the fiber.

14 Whether the outer coating comprises a polymer jacket or a carbon film, the outer coating  
15 must be spatially patterned appropriately, thereby yielding a mask substantially covering the  
16 desired resonator segment upon etching. The mask may preferably be patterned by spatially  
17 selective laser machining of the outer coating, removing the outer coating from the adjacent  
18 portions and leaving the outer coating on the resonator segment. A polymer jacket outer coating  
19 may be laser machined using a UV-emitting excimer laser. A carbon film outer coating may be  
20 laser machined using a pulsed laser (presumably ablatively) or with a substantially continuous  
21 laser (presumably thermally). During laser machining to pattern the mask the optical fiber may  
22 preferably be rotated about its long axis to produce ring-like mask patterns on the fiber. This  
23 rotation should preferably be concentric (thereby substantially minimizing any "orbital" motion  
24 of the fiber cross-section about the rotation axis, also referred to as centration error). This may  
25 preferably be achieved by using a rotational guide such as a vacuum V-block for defining a fiber  
26 rotation axis. Sufficient negative pressure may be applied to maintain low centration error  
27 during rotation, but must be sufficiently low to allow smooth rotation at a sufficiently high speed  
28 (typically 100-300 rpm). Paired V-blocks may be employed, one on each side of the fiber length  
29 to be machined, to enhance the positioning stability of the rotating fiber. Alternatively, a  
30 capillary tube or fiber ferrule (singly or in pairs) may be used in any equivalent manner to align  
31 the fiber for rotation and laser machining. (Hereinafter, use of a capillary for fiber alignment as

described herein shall be understood to equivalently encompass use of a fiber ferrule). A capillary tube should be chosen having an inner diameter closely matching the optical fiber diameter. For example, the carbon-coated fiber mentioned hereinabove has a nominal diameter of 125  $\mu\text{m}$ . Capillary tubing is commercially available (0.4  $\lambda$  supplied by Drummond Scientific, Inc.) having an inner diameter of  $126.4 \pm 0.3 \mu\text{m}$ , making it ideal for concentrically aligning and rotating the fiber during laser machining. This V-block, capillary or fiber ferrule alignment technique for substantially concentric rotation of the optical fiber may be employed during any other fabrication step requiring such rotation of the optical fiber, as set forth hereinbelow. Similar use of a capillary for substantially concentric rotation of an optical fiber during laser processing is described in a publication of Presby et al. (Applied Optics **29** 2692 (1990)), said publication being hereby incorporated by reference in its entirety as if fully set forth herein. While remaining within the scope of inventive concepts disclosed and/or claimed herein, any suitable means may be employed for substantially concentric rotation of the optical fiber during laser machining, including but not limited to V-blocks, a capillary tube, a fiber ferrule, an alignment chuck, an alignment jig, an indexed fiber holder, and so forth, either singly or in pairs.

It should be noted that the rotary bearing and rotary actuator may be used to form full rings on the optical fiber by fully rotating the fiber under substantially continuous exposure to the laser beam (or other focused processing beam; ion, electron, atomic, plasma, and so forth). However, it also be desirable to provide only partially-machined rings on the optical fiber. These partial rings may be employed to produce asymmetric structures on the fiber upon subsequent processing. Partial rings may be generated by only partially rotating the fiber as it is exposed to the laser beam. Alternatively, the laser beam may be synchronously modulated (i.e., shuttered) as the fiber fully rotates, thereby only exposing a partial ring of the fiber. Such synchronous modulation may be readily implemented using a opto-interrupt switch or functionally similar device to couple beam shuttering to fiber rotation

In a preferred method for precisely machining rings in a hermetic carbon mask material, the carbon coated fiber may be threaded through a first V-block, capillary tube or other rotation guide. A relatively long segment of the carbon coated fiber (as long as several inches or more) may extend from the first end of the capillary, and is coupled to a rotation device. The rotation device must produce controlled, substantially uniform rotary motion of the fiber with minimal thrust error. (The term "thrust error" refers to any unwanted longitudinal motion that may

1 accompany the desired rotary motion. The thrust error that is synchronous with the rotation  
2 results in a tilt of the machined ring with respect to a plane perpendicular to the fiber axis, an  
3 effect which may be used to intentionally produce tilted rings. Provided that the thrust error is  
4 kept small, less than about 10% of the ring diameter, the ring tilt will not result in substantial  
5 undesirable radiative loss from the ring segment. Control of the tilt may be exploited to tune the  
6 resonant frequency of a ring fabricated from an optical fiber of a given diameter, since the  
7 perimeter path length, and hence the optical resonance frequencies, of the ring can be varied by  
8 varying the ring tilt angle by adjusting the thrust "error". A prototype system (Fig. 4) has been  
9 successfully constructed using a precision drill press (Cameron Micro Drill), but a preferred  
10 embodiment, also successfully prototyped, comprises an air bearing spindle 400 (Professional  
11 Instruments 4B) belt-driven by a stepper motor/encoder system (not shown). An air-bearing  
12 spindle may be preferred as having the smallest achievable thrust error currently available  
13 commercially (as small as 25 nm; thrust error of about 1  $\mu\text{m}$  or less is generally sufficient for the  
14 present invention; thrust error as high as 10  $\mu\text{m}$  may be tolerated under less demanding  
15 circumstances). Carbon coated fiber 402 may be secured substantially co-axially to the air  
16 bearing spindle (optionally cemented within a capillary tube 404 and the capillary tube secured  
17 to air bearing spindle 400). Without departing from inventive concepts disclosed and/or claimed  
18 herein, other devices may be equivalently employed to produce the desired rotary motion,  
19 including but not limited to rotation stages, stepper-motor-driven rotators, servo-motor-driven  
20 rotators, and the like. As the air-bearing spindle or other rotary device rotates the carbon-coated  
21 fiber, the fiber rotates within a vacuum V-block, capillary tube, or other rotation guide 408 with  
22 low centration error. As long as both fiber and the rotation guide are substantially  
23 uncontaminated, this rotation of the fiber within the capillary will not damage the carbon coating.  
24 If desired, it may be possible to drive air or other gas through a capillary around the rotating fiber  
25 to serve as an air-bearing. The alignment fiber is substantially rigidly mounted in a standard  
26 fiber chuck or other similar device 409, and a relatively short segment of the carbon-coated fiber  
27 402 extends beyond the second end of the rotation guide 408. A second rotation guide may be  
28 employed on the far end of the fiber to further limit lateral motion during rotation. A microscope  
29 objective 410 (60X in the prototype; others may be used as appropriate) for delivering a laser  
30 beam for laser machining may be mounted on a precision 3-axis translator 412 for precise  
31 positioning relative to the carbon-coated fiber.

A laser beam 414 from an argon ion laser (typically multi-line visible output, mainly 488 nm and 514 nm, between about 10 mW and about 100 mW average power) or a continuous wave frequency-doubled YAG laser (visible output, at 532 nm, between about 10 mW and about 100 mW average power) is brought to a spot size between about 0.2  $\mu\text{m}$  and about 3  $\mu\text{m}$ , preferably about 0.5-1.0  $\mu\text{m}$ , by the objective 410 onto the surface of the fiber 402 as it rotates, thereby removing the carbon coating from the fiber (presumably by a thermal mechanism). A beamsplitter 416 in the laser beam path allows back-scattered and/or back-reflected laser light from the fiber to be imaged at 418 in order to adjust the focus of the laser beam sufficiently precisely relative to the surface of the fiber. The laser beam need not necessarily be focused at the surface of the fiber (although it could be, if desired). Use of a microscope objective is important for several reasons. The highly convergent beam enables the machining of rings in the hermetic carbon coating as small as 0.5 to 3  $\mu\text{m}$  wide with relatively sharp edges, which in turn reduces the roughness of the edges of the resonator segment produced by subsequent etching. A tight focus on the machined surface of the fiber also insures that the laser beam transmitted through the fiber will be sufficiently defocused when it reaches the opposite surface of the fiber so that none of the coating will be removed from the opposing surface, which would degrade the precision of the edges of the machined rings. The centration error of the carbon-coated fiber within the capillary tube is typically sub-micron, well within the depth-of-focus of the tightly focused laser beam (typically a few microns). It has also been observed that microscopic defects may occur in the portions of the carbon coating left behind after laser machining, resulting in unwanted etched spots and edge roughness in the resonator fiber segment and degradation of the performance of the resulting WGM resonator. This effect is believed to be due to excessive heating of the carbon-coated fiber during laser exposure, which causes damage to the carbon coating and/or the underlying silica adjacent to the carbon being exposed. In addition, exposure of the carbon-coated fiber at high power (greater than about 30 mW) causes texturing of the silica underlying the exposed carbon, presumably due to melting of the underlying silica. It has been observed that reducing the optical power of the exposing laser beam to 10-25 mW substantially eliminates the thermal damage problem as well as the surface texturing problem. It has also been observed that flowing gas ( $\text{O}_2$ ,  $\text{N}_2$ , and ambient air have been used successfully, although  $\text{O}_2$  may be preferable) around the fiber as it is machined seems to mitigate the defect problem.



1           It should be noted that a microscope objective may not be required for sufficiently precise  
2    machining of rings in the carbon coating. In general, if the optical fiber is substantially  
3    transparent to the wavelength used for machining the carbon coating (or other fiber outer  
4    coating), then the beam must be highly convergent (with an objective or similar optical assembly  
5    having an NA greater than about 0.3, preferably around one) so that the transmitted beam is too  
6    diffuse to damage the fiber outer coating on the opposite side of the fiber. However, if the fiber  
7    is not transparent to the laser-machining wavelength (157 nm from an F<sub>2</sub> excimer laser, for  
8    example, or if the fiber is a hollow fiber filled with material non-transparent at the laser-  
9    machining wavelength, or if the fiber is doped to render it non-transparent at the laser-machining  
10   wavelength), then damage to the opposite side of the fiber is no longer an issue, and the optical  
11   assemblies having longer working distances (i.e., smaller NA) may be employed. This is a  
12   general principle that may be applicable to other laser-machining steps set forth hereinbelow.  
13   Any laser source suitable for laser machining (known in the art or hereafter developed) may be  
14   employed while remaining within the scope of inventive concepts disclosed and/or claimed  
15   herein, for any laser machining step disclosed herein.

16           For silica or silicate-based optical fibers, aqueous hydrofluoric acid (HF) is an effective  
17    etching agent for removal of material from the adjacent segments of the optical fiber. The  
18    amount of material removed can be precisely controlled by controlling the etching time, etchant  
19    concentration and/or pH, and/or temperature. The etched surfaces are quite smooth and  
20    substantially free of irregularities, thereby minimizing optical scatter from the etched surfaces of  
21    the circumferential-mode optical resonator. It should be noted that as the etching process  
22    proceeds radially, exposure of transverse edges of the resonator segment become exposed to the  
23    etchant and come under attack. The thickness of the resulting resonator segment is therefore  
24    somewhat smaller than the width of the initial ring-shaped mask, and the edge of the resonator  
25    segment may be slightly concave. The concentration of HF used to etch the optical fiber may be  
26    between about 5% and about 50% HF buffered with NH<sub>4</sub>F, should preferably be between about  
27    7% and about 8% HF and between about 30% and about 40% NH<sub>4</sub>F, and most preferably about  
28    7.2% HF and 36% NH<sub>4</sub>F. The most preferred concentration yields an etch rate of about 80  
29    nm/min, and is available commercially (Transene Company, Inc.). Another suitable HF  
30    concentration is 1 part 40% HF(aq) combined with 10 parts 40% NH<sub>4</sub>F(aq), as disclosed in the  
31    publication of Eisenstein et al. (Applied Optics **21** 3470 (1981), said publication being

1 incorporated by reference in its entirety as if fully set forth herein. Any of these disclosed  
2 concentrations may be employed during any other fabrication step requiring an HF etch, as set  
3 forth hereinbelow. While remaining within the scope of inventive concepts disclosed and/or  
4 claimed herein, any suitable wet or chemical etching agent (either known in the art or hereafter  
5 developed) may be used to reduce the diameter of the adjacent portions or other portions of the  
6 fiber. Alternatively, dry or reactive ion etching procedures, employing suitable etch masks  
7 (metal masks or polymer masks, for example), may be used to reduce the diameter of the  
8 adjacent portions or other portions of the fiber. After etching, the mask may be removed by any  
9 of a variety of methods, including but not limited to non-spatially-selective laser machining,  
10 chemical/solvent removal, thermal removal (i.e., burning), exposure to an electrical discharge,  
11 plasma ashing, ion sputtering, and other suitable methods for removing the mask (known in the  
12 art or hereafter developed).

13 It may be preferable, however, to leave a portion of the mask on the resonator fiber.  
14 After etching, the same cylindrical laser machining techniques used to produce the mask may be  
15 employed to spatially-selectively remove the mask material from the resonator segment 100,  
16 while leaving the mask on un-etched portions of surrounding fiber segments 200 (Fig. 3). The  
17 etched grooves between the resonator segment and the surrounding segments are preferably  
18 between about 5  $\mu\text{m}$  and about 10  $\mu\text{m}$  wide, for a resonator segment between about 2  $\mu\text{m}$  and  
19 about 4  $\mu\text{m}$  wide. By leaving the mask material (generally optically absorbing and/or scattering)  
20 on the surrounding fiber segments, delocalized modes supported by the resonator fiber may be  
21 selectively suppressed, while leaving the desired circumferential optical mode substantially  
22 undisturbed. The result is a clean resonance spectrum for the circumferential resonator, and little  
23 or no cross-talk and/or undesirable optical loss in resonant optical control devices employing  
24 fiber-ring resonators according to the present invention. Such mode suppression may also be  
25 desirable for a coupled set of multiple fiber-ring resonators on a single resonator fiber.  
26 Alternatively, delocalized-optical-mode suppressors may be provided on surrounding segments  
27 of the resonator fiber as a separate fabricating step, regardless of the method used to fabricate the  
28 fiber-ring resonator. An optical absorber may be deposited or an optical scatterer may be  
29 deposited, machined, etched or otherwise fabricated using methods described herein, on portions  
30 of the surrounding segments of the resonator fiber (Fig. 10). Delocalized-optical-mode  
31 suppressors may also be employed near other structures fabricated on an optical fiber, such as

1 alignment members and fiber-taper positioners as described hereinbelow. Such structure may  
2 support unwanted and potentially interfering delocalized optical modes. These modes may be  
3 suppressed by providing absorbing or scattering members on the fiber near the structure. Such  
4 mechanical structures may also be fabricated to extend only partially around the fiber, also  
5 mitigating the problem of delocalized-optical modes.

6 An alternative method for dealing with delocalized optical modes is the use of optical  
7 fiber having an absorbing and/or scattering core. Such a core serves to suppress any delocalized  
8 optical modes while leaving desired circumferential optical modes substantially undisturbed.  
9 Such a fiber may be manufactured with an absorbing and/or scattering core, or hollow-core  
10 optical fiber may be employed, and the hollow core filled with absorbing and/or scattering  
11 material of any suitable type.

12 As an alternative to the mask-and-etch procedure described hereinabove, the diameters of  
13 the adjacent portions may be reduced by direct laser machining of the fiber to remove optical  
14 fiber material (Fig. 5). Substantially concentric rotation may preferably be employed during  
15 laser machining using one or more vacuum V-blocks as described hereinabove. Laser machining  
16 may be performed without removing a fiber jacket (if present), in which case the fiber jacket is  
17 removed from the adjacent portions during laser machining and the portion of the jacket  
18 remaining on the resonator segments may be removed after laser machining by any appropriate  
19 method. Alternatively, the fiber jacket (if present) may be removed from the resonator segment  
20 and the adjacent portions prior to laser machining. A fluorine excimer laser emitting at 157 nm  
21 may preferably be used for laser machining a silica or silicate-based optical fiber, although other  
22 appropriate laser sources (pulsed UV-emitting laser sources, amplified and/or modelocked  
23 titanium:sapphire lasers, pulsed CO<sub>2</sub> lasers, and so forth) may be employed (particularly for  
24 other types of optical fiber) while remaining within the scope of inventive concepts disclosed  
25 and/or claimed herein. The earlier discussion of a low NA laser-beam-delivery optical assembly  
26 (if the fiber is substantially opaque at the laser-machining wavelength) versus a high NA laser-  
27 beam-delivery optical assembly (if the fiber is substantially transparent at the laser-machining  
28 wavelength) applies to direct machining of the optical fiber (a high NA assembly, i.e., a  
29 microscope objective, is shown in Fig. 5 and is exemplary only). Following laser machining the  
30 fiber, including the resonator segment and the adjacent portions, may be polished to reduce  
31 and/or eliminate laser-machining-induced irregularities on the circumferential-mode resonator.

1 Such irregularities may act as light scattering centers, thereby degrading the performance (Q-  
2 factor, for example) of the circumferential-mode resonator. Suitable polishing techniques may  
3 include but are not limited to spatially non-selectively etching, thermal polishing with a flame or  
4 CO<sub>2</sub> laser, polishing with an electrical arc or fusion splicer, and so forth.

5       Once the adjacent portions have been reduced in diameter relative to the resonator  
6 segment, the diameter of the resonator segment may be reduced to achieve a desired  
7 circumferential-mode resonant frequency and/or a desired free spectral range between modes,  
8 while producing a diameter of the resonator segment 100 the desired amount larger than the  
9 diameter of the adjacent portions 200. The desired free spectral range will be determined by the  
10 wavelength spacing of channels in the particular WDM standard in use and the number of these  
11 channels desired to be modulated by an optical power control device employing circumferential-  
12 mode resonator according to the present invention. The circumferential-mode free spectral range  
13 divided by the channel spacing yields the approximate number of channels that may be  
14 simultaneously modulated by a single device or a series of devices on a single transmission  
15 optical fiber. Resonator segment diameters below about 10  $\mu\text{m}$  may result in a circumferential-  
16 mode resonator Q-factor that is unacceptably low. The thickness of the resonator segment  
17 should preferably be between about 1  $\mu\text{m}$  and about 10  $\mu\text{m}$ , and most preferably between about 2  
18  $\mu\text{m}$  and about 4  $\mu\text{m}$ . The diameter of the resonator segment may be reduced by spatially non-  
19 selective etching, employing aqueous HF (as described hereinabove) or other suitable etching  
20 agent (Fig. 6). This may also reduce the thickness of the resonator segment by etching the edges  
21 of the resonator segment, and the resulting edges may be slightly concave (as described earlier).  
22 Alternatively, the diameter of the resonator segment may be reduced by laser machining as  
23 described hereinabove and shown in Fig. 5 (and may preferably include use of a V-block,  
24 capillary tube, or fiber ferrule for substantially concentric rotation of the optical fiber during  
25 laser machining, as described hereinabove). Relatively fine-tuned selection of the  
26 circumferential-mode resonator diameter and/or thickness may be required to select a particular  
27 wavelength component from among the wavelength components present in a wavelength-  
28 division-multiplexed (WDM) optical signal. This process may be referred to a resonator  
29 trimming. For example, to fabricate a circumferential-mode resonator selectively resonant with a  
30 single channel (typically about 10 GHz wide, for example) from among the 50 GHz- or 100  
31 GHz-spaced WDM channels present within the ca. 80 nm overall bandwidth of the erbium

1 amplifier C and L bands (centered around 1550 nm), the diameter must controlled to within  
2 about  $\pm 5$  nm ( $\pm 10$  GHz for the resonator frequency), requiring control of the etch time on the  
3 order of about  $\pm 1$  second to about  $\pm 10$  seconds. Such precision of fabrication may be readily  
4 achieved using standard techniques of laser machining or other precision machining methods, or  
5 by careful control of etch conditions (etchant concentration and/or pH, temperature, and/or  
6 etching time). Appropriate dilution of the etchant may yield slower etch rates, thereby enabling  
7 enhanced precision for the final diameter of an etched resonator segment.

8 An alternative process may be employed to trim a fiber-ring resonator to a desired  
9 resonance frequency. It is well-know that germano-silicate optical fiber (including hydrogen  
10 loaded and boron-co-doped germano-silicate optical fiber) is photosensitive. This phenomena  
11 has been used to write Bragg gratings into an optical fiber, for example. Irradiation leads to an  
12 increase in the refractive index of the material. By exposing a fiber-ring resonator, fabricated  
13 with a photosensitive germano-silicate resonator fiber, to visible or UV irradiation, the  
14 resonance frequencies may be precisely adjusted. The irradiation may be done using a focused  
15 visible or UV source (such as an excimer laser, ion laser, or doubled, tripled, or quadrupled  
16 solid-state laser, or other visible or UV source), or may be done using surface or shadow mask  
17 techniques and an unfocused visible or UV source. It is desirable to monitor the resonance  
18 spectrum of the fiber-ring during trimming, and this may be done by monitoring the transmission  
19 spectrum of a fiber taper or other evanescent waveguide coupled to the fiber-ring resonator  
20 during trimming. A particularly elegant solution involves delivering the visible or UV  
21 illumination through the same fiber taper used to monitor the resonance frequency. The length  
22 of fiber that may be used in this way is limited, due to the relatively high loss of most optical  
23 fiber in the UV. This visible or UV trimming technique may be used on single fiber-ring  
24 resonators, or may be applied to a coupled system of fiber-ring resonators, either individually or  
25 as a group. To individually monitor one resonator from a coupled system, it is necessary to  
26 suppress the resonant modes of the other resonators in the system, for example, by contacting all  
27 other resonators except the one monitored with a loss probe. It has been observed that for long  
28 term stability of the trimming, thermal annealing of the fiber-ring is necessary. The refractive  
29 index (and therefore the resonance frequency) of the fiber-ring may shift slightly during the  
30 annealing process. Some experimentation is typically required to establish an exposure  
31 calibration that accounts for the frequency shift during annealing.

Alternatively, a desired circumferential-mode resonant frequency may be obtained by fabrication of a suitably tilted resonator segment as set forth hereinabove. The resonant frequency shift varies as  $\sin^2 \theta$ , where  $\theta$  is the angle between the tilted ring and a plane perpendicular to the longitudinal axis of the optical fiber. Controlled longitudinal motion of the fiber during rotation as the fiber is machined may be employed to impart the desired tilt angle on the resonator. It should be noted that controlled longitudinal motion of the fiber or laser focusing objective may be employed to produce sinusoidal rings, or rings having any desired curvilinear shape. This may be accomplished by including a longitudinal actuator in the fiber rotation assembly, or alternatively by utilizing the longitudinal positioner 412 of the objective lens 410.

It should be noted, however, that stable operation of a resonant optical power control device according to the present invention may require temperature stabilization of the circumferential-mode resonator. It has been observed that the resonance frequencies of a circumferential-mode resonator based on silica microsphere varies with temperature by about 2.5 GHz/°C, and presumably a similar quantity (modified by the appropriate geometric factor) applies to disk or ring circumferential-mode resonators fabricated from silica optical fiber according to the present invention, thereby necessitating control of the circumferential-mode temperature. However, this also affords the opportunity to control the resonant wavelength of the circumferential-mode resonator by varying the temperature at which the circumferential-mode resonator is maintained/stabilized. This may be accomplished with no substantial additional cost or complexity, since temperature stabilization is required even if temperature tuning of the resonant frequencies is not desired. Any suitable method for monitoring and controlling the circumferential-mode temperature (known in the art or hereafter developed) may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein. A thermo-electric cooler may be well-suited for controlling the resonator temperature, although other temperature control devices may serve as well.

Instead of decreasing the diameter of the adjacent portions, the resonator segment may alternatively be enlarged by deposition of a substantially annular ring of material on the optical fiber. This may preferably be accomplished by the process of: 1) providing the adjacent portions with a mask while leaving the resonator segment substantially exposed; 2) spatially-selectively depositing material on the resonator segment, thereby increasing its diameter; and 3) removing the mask from the adjacent portions (Fig. 7). In particular, it may be preferred to

1 provide the mask by spatially-selective removal of an outer coating 300 of the optical fiber from  
2 the resonator segment. This spatially-selective removal of the outer coating of the optical fiber  
3 may be performed by laser machining as already described herein and shown in Figure 5. The  
4 outer coating of the fiber may comprise the polymeric jacket of the fiber, or may comprise any  
5 suitable mask material deposited on the fiber prior to the mask-providing step. A UV-emitting  
6 excimer laser may preferably be employed for laser machining of the polymeric jacket, although  
7 any other suitable laser source may be employed for laser machining a particular mask material.  
8 The fiber may be rotated during laser machining and may be mounted in a rotation guide to  
9 provide substantially concentric rotation, as already described elsewhere herein.

10 As shown in Fig. 7, once the mask has been provided substantially covering the adjacent  
11 portions while leaving the resonator segment 100 substantially exposed, material 310 may be  
12 spatially-selectively deposited on the resonator segment by any of a variety of suitable  
13 techniques. Chemical vapor deposition (CVD) may be a preferred deposition technique,  
14 although other techniques may be employed (often depending on the nature of the material being  
15 deposited) while remaining within the scope of inventive concepts disclosed and/or claimed  
16 herein. Such techniques may include but are not limited to: deposition of self-assembled  
17 monolayers (SAM's), thermal evaporation/deposition, sputter deposition, epitaxial techniques,  
18 beam assisted deposition techniques (laser, ion, electron, x-ray, radical, molecular, atomic, or  
19 other activation beams may be employed) combinations thereof, and/or functional equivalents  
20 thereof. The fiber may preferably be rotated during deposition of the material, thereby resulting  
21 in substantially uniform deposition of material around the circumference of the optical fiber.

22 The fiber may be mounted within V-blocks, capillary tubes, or fiber ferrules singly or in pairs,  
23 thereby enabling substantially concentric rotation of the fiber for substantially uniform  
24 deposition. After deposition of the material 310, the mask (i.e., outer coating 300) may be  
25 removed by any suitable mechanical, chemical, optical, or other process suitable for the  
26 particular mask employed. The deposited material 310 forms a substantially annular ring on the  
27 circumference of the optical fiber, and eventually forms at least a portion of the circumferential-  
28 mode optical resonator segment 100. Shadow-masked deposition, focused material beam  
29 deposition, or focused-beam-assisted deposition may be employed as an alternative to surface-  
30 masked deposition.

1 A dielectric material may typically be preferred as the deposited material. Suitable  
2 materials may include, but are not limited to: silicate, rare-earth-doped glasses, semiconductor-  
3 doped glasses, amorphous semiconductors, chalcogenide glasses, amorphous silicon alloys,  
4 combinations thereof, and/or functional equivalents thereof. It may be preferred to use a material  
5 having substantially fixed optical properties (silica, for example), thereby yielding a  
6 circumferential-mode resonator having substantially fixed properties. Alternatively, it may be  
7 desirable to deposit material that enables subsequent modification and/or modulation of the  
8 circumferential-mode resonator properties. Such a material may comprise a pure material, a  
9 mixture of materials, a secondary material deposited as a thin film coating on a primary material,  
10 and/or a primary material having one or more secondary materials as dopants therein. Materials  
11 may be selected, designed, and/or formulated to enable controlled modulation of optical  
12 properties of the circumferential-mode resonator, including but not limited to: optical loss,  
13 optical gain, optical coupling to/from the circumferential-mode resonator, resonant frequencies,  
14 free spectral range, and so forth. The materials used may include, but are not limited to:  
15 dielectric materials, electro-optic materials, electro-absorptive materials, non-linear optical  
16 materials, semiconductor materials, metals, polymers, combinations thereof, and/or functional  
17 equivalents thereof. Application of electronic, optical, and/or other control signals to the  
18 circumferential-mode resonator may be employed for modulation of one of more of the  
19 circumferential-mode optical properties.

20 Following deposition of material on the resonator segment to form the circumferential-  
21 mode resonator, the diameter of the circumferential-mode resonator may be reduced by removal  
22 of material to alter resonant frequencies and/or the free spectral range of the circumferential-  
23 mode resonator using etching, laser machining, and/or other suitable techniques as already  
24 described herein (Figs. 5 and 6). Visible or UV trimming may also be employed for suitable ring  
25 materials. Preferred ranges for resonator segment diameter, thickness, and free spectral range  
26 have been given hereinabove.

27 The refractive index of the fiber may be the property that differs between the resonator  
28 segment and the adjacent portions of the surrounding segments of the resonator fiber. A  
29 transverse resonator segment having a refractive index as little as  $10^{-5}$  greater than the refractive  
30 index of the adjacent portions may enable confinement of a circumferential-mode optical wave  
31 propagating around the circumference of the resonator segment at least partially within the fiber



1 segment. The refractive index of the resonator segments may be increased by spatially-  
2 selectively exposing a photosensitive resonator fiber to visible or UV irradiation (increasing the  
3 optical pathlength of the resonator segment), or the chemical composition of the resonator  
4 segment may be spatially-selectively altered to yield a larger refractive index. Generation of this  
5 refractive index differential may be accomplished while producing fewer irregularities (such as  
6 arise during laser machining) on the optical fiber that could lead to scattering during use of the  
7 device and degradation of the performance characteristics of the circumferential-mode resonator  
8 (such as the resonator Q-factor).

9 In a method for fabricating a circumferential-mode resonator according to the present  
10 invention, the optical fiber is a germano-silicate fiber or other visible- or UV-sensitive optical  
11 fiber (including hydrogen-loaded germano-silicate or boron-co-doped germano-silicate), and the  
12 resonator segment 100 is spatially-selectively irradiated with visible or UV light, thereby  
13 increasing the refractive index of the resonator segment 100 relative to the adjacent portions 200  
14 (shown in cross-section in Fig. 8A, where the density of the stippled hatching reflects the relative  
15 refractive index, density, and/or a dopant concentration). A UV-emitting excimer laser may be  
16 particularly well-suited for this purpose, however, any suitable visible or UV source sufficiently  
17 intense and/or focusable may be employed while remaining within the scope of inventive  
18 concepts disclosed and/or claimed herein, including but not limited to an ArF excimer laser (193  
19 nm), a KrF excimer laser (248 nm) and an argon ion laser (334 nm). Various masks 810 may be  
20 employed to obtain the desired spatial variation of refractive index, including phase masks and  
21 amplitude masks. Such techniques are disclosed in: Starodubov et al., Optics Letters, **22** 1086  
22 (1997); Hill et al., Applied Physics Letters, **62** 1035 (1993); and Hill et al., Optics Letters, **19**  
23 1314 (1994). Each of these publications is hereby incorporated by reference in its entirety as if  
24 fully set forth herein. Alternatively, the spatially selective irradiation may be accomplished  
25 without masking, but by controlling the spatial profile of the irradiating beam (see discussion  
26 above pertaining to high NA and low NA optical assemblies). The fiber may be rotated during  
27 irradiating, and a V-block, capillary, or fiber ferrule (singly or in pairs) may be employed to  
28 mount the fiber and provide substantially concentric rotation as described earlier herein. The  
29 photo-induced refractive index change need not necessarily extend all the way through the fiber  
30 (as shown in Figures 8A, 8B, and 8C), but may comprise a ring of higher-index fiber material  
31 around the circumference of the resonator segment. The susceptibility of germano-silicate to

1 densification by visible or UV irradiation may be enhanced by hydrogen loading the germano-  
2 silicate material prior to visible or UV irradiation, or by boron co-doping. Hydrogen loading  
3 may be accomplished by exposing the germano-silicate optical fiber to about 2500 psi of H<sub>2</sub> gas  
4 for a period of about one week, for example. Other H<sub>2</sub> pressures and exposure times may also be  
5 suitable. Germano-silicate fiber of a sufficiently large diameter (greater than about 50  $\mu$ m, for  
6 example) for fabricating circumferential-mode resonator according to the present invention may  
7 be obtained commercially, or may be produced by stripping the lower index cladding material  
8 from a multi-mode germano-silicate-core optical fiber. Such multi-mode fibers may have core  
9 diameters of about 50  $\mu$ m or more, so that stripping the cladding may leave a fiber having a  
10 diameter sufficiently large to produce the circumferential-mode resonator therefrom. The  
11 cladding may be stripped by any suitable means, including but not limited to laser machining  
12 (possibly utilizing a capillary for mounting and substantially concentrically rotating the optical  
13 fiber during laser machining) and etching (with aqueous HF or other suitable etching agent).

14 The refractive index of the resonator segment relative to the adjacent portions may  
15 alternatively be spatially-selectively increased by altering the chemical composition of the  
16 resonator segment by a method comprising the steps of: 1) providing a mask that substantially  
17 covers the adjacent portions while leaving the resonator segment substantially exposed; 2)  
18 doping the resonator segment with a suitable doping material; and 3) removing the mask from  
19 the adjacent portions (Figure 8A). The same methods described hereinabove for producing  
20 masks for spatially-selective deposition of material onto the fiber may also be employed for  
21 producing a mask for spatially-selective doping of the optical fiber, including use of an outer  
22 coating of the optical fiber as the mask material 810. Alternatively, the outer coating may  
23 instead be spatially-selectively removed from the adjacent portions 200 and left on the resonator  
24 segment 100, and the mask material 810 may then be deposited onto the adjacent portions 200.  
25 The resonator segment 100 may then be spatially-selectively doped after removal of the  
26 remaining outer coating therefrom. The mask material 810 may be a metal, a dielectric material,  
27 a polymer mask, or other suitable material. At the final mask removal step, portions of the mask  
28 may be left on the surrounding segments of the resonator fiber to serve a delocalized-optical-  
29 mode suppressors, as described hereinabove.

30 After providing the mask on the adjacent portions, the resonator segment may be doped  
31 in any of a variety of suitable techniques, including but not limited to: ion implantation of the

1 doping material into the fiber; and simple diffusion of the doping material (by exposure of the  
2 masked fiber to dopant vapor or liquid; or by deposition of solid dopant onto the masked fiber)  
3 into the optical fiber. As in various deposition and laser machining steps described hereinabove,  
4 the optical fiber may be rotated during the doping step to obtain substantially uniform doping of  
5 the optical fiber around its circumference, and the fiber may be mounted in a V-block or  
6 capillary tube to provide substantially concentric rotation of the fiber during doping. The doped  
7 region need not necessarily extend all the way through the fiber (as shown in Figs. 8A, 8B, and  
8 8C), but may comprise a ring of doped fiber material around the circumference of the resonator  
9 segment. The fiber may be doped with any of a variety of suitable materials for increasing the  
10 refractive index of the optical fiber while remaining within inventive concepts disclosed and/or  
11 claimed herein. Preferred materials for use as the doping material include but are not limited to  
12 germanium, titanium, boron, aluminum, phosphorus, erbium, ytterbium, praseodymium, thulium,  
13 holmium, neodymium, europium, cerium, and other rare earth elements. In addition to altering  
14 the refractive index of at least a portion of the resonator segment, an appropriately chosen doping  
15 material may comprise a material that enables modification of the optical properties of the  
16 circumferential-mode resonator, such properties including optical loss, optical gain, optical  
17 coupling to/from the resonator, and resonant frequencies. Such doping materials may include  
18 but are not limited to materials for rendering the resonator segment: electro-optic, electro-  
19 absorptive, optically non-linear, combinations thereof, and/or functional equivalents thereof.  
20 Such doping materials may enable modulation of optical properties of the circumferential-mode  
21 resonator by application of optical, electronic, and/or other control signals to the circumferential-  
22 mode doped with the doping material. The resonator segment may alternatively be spatially-  
23 selectively doped using shadow-masked doping, focused-material-beam doping, or focused  
24 beam-assisted doping as an alternative to surface-masked doping.

25 In addition to producing a circumferential-mode resonator segment by spatially-  
26 selectively increasing the refractive index, spatially-selective doping may be employed to  
27 produce a circumferential-mode resonator by an alternative technique (Fig. 8C). Certain dopants  
28 (germanium, for example) are known to decrease the etch rate of silica. By spatially-selectively  
29 doping a resonator segment 100 of a silica fiber with germanium prior to etching, a relatively  
30 larger-diameter resonator segment 100 is produced by the etching process, since the adjacent  
31 portions 200 are etched at a faster rate. Careful control of the germanium doping level and the

1 etching conditions (concentration, pH, temperature, etching time, and so forth) allow control  
2 over the properties of the resulting circumferential-mode resonator segment.

3 Laser machining has been set forth as a preferred method for spatially-selective removal  
4 of material from the optical fiber at various points in the cylindrical processing of the  
5 circumferential-mode optical resonator (for patterning etch masks, deposition masks, diffusion  
6 and/or doping masks, and so forth). While remaining within the scope of inventive concepts  
7 disclosed and/or claimed herein, other methods for patterned removal of material from the  
8 optical fiber may be employed, including but not limited to: lithographic methods, optical  
9 patterning of photosensitive materials and/or photo-resists, beam patterning of other resists (ion,  
10 electron, atomic, molecular, x-ray, or other beams), beam-assisted processes, surface-masked  
11 processes, shadow-masked processes, mechanical techniques, electric or plasma discharge  
12 techniques, combinations thereof, and/or functional equivalents thereof.

13 As noted above, in a typical application of a resonant optical power control device  
14 according to the present invention, the circumferential-mode resonator is optically coupled to a  
15 transmission optical waveguide, typically a second optical fiber (“transmission fiber-optic  
16 waveguide”) in order to enable control of transmission of optical power through the second  
17 optical fiber. In a preferred embodiment of a resonant optical power control device according to  
18 the present invention, the circumferential-mode resonator and a second optical fiber are  
19 positioned on an alignment device to enable reproducibly established and stable maintained  
20 evanescent optical coupling between the second optical fiber and the circumferential-mode  
21 resonator. Reproducible optical coupling between the second optical fiber and the resonator is  
22 highly desirable to enable efficient and consistent fabrication of the resonant optical power  
23 control device. Accordingly, the circumferential-mode optical resonator may preferably be  
24 provided with an alignment member (alternatively referred to as an “indexing member”) on at  
25 least one of the surrounding segments 200 for enabling reproducible optical coupling of the  
26 resonator segment 100 and the second optical fiber when they are positioned on the alignment  
27 device. Preferred alignment or indexing members that may be provided on one or more of the  
28 surrounding segments 200 may comprise circumferential grooves 220 and/or circumferential  
29 annular flanges 210 for engaging corresponding alignment or indexing members that may be  
30 provided on the alignment device (Figs. 9A and 9B). Other suitable alignment or indexing  
31 members may be employed while remaining within the scope of inventive concepts disclosed

1 and/or claimed herein. Flanges 210 and/or grooves 220 may be fabricated by spatially-selective  
2 deposition and/or removal of material from the optical fiber. A groove may be produced by  
3 removing material from the groove location, or alternatively by depositing material on each side  
4 of the groove location. A flange may be produced by depositing material on the flange location,  
5 or alternatively by removing material from each side of the flange location. Spatially-selective  
6 deposition and/or removal of material to produce flanges, grooves, and/or other alignment  
7 structures may be performed by laser machining, masking, etching, and/or other suitable  
8 cylindrical processing methods as already set forth hereinabove. Deposited material may  
9 comprise the same material as the adjacent portion, and/or any other material suitable for  
10 depositing on the adjacent portion and having properties suitable for use as an alignment  
11 structure (for example, mechanical strength, adhesion to the adjacent portion, chemical  
12 compatibility, and so forth). Examples may include but are not limited to: outer coating material  
13 of the fiber, fiber jacket material (polymeric jacket material, for example), fiber cladding  
14 material, fiber core material, and/or other functionally equivalent materials. Material removed  
15 from the fiber may comprise portions of: an outer coating material of the fiber, fiber jacket  
16 material (polymeric jacket material, for example), fiber cladding material, and/or fiber core  
17 material.

18 The alignment members on the resonator fiber may be capable of supporting undesirable  
19 optical modes that could interfere with the resonant modes of the fiber-ring resonator. It may  
20 therefore be desirable to provide the resonator fiber with delocalized-optical-mode suppressors in  
21 a manner similar to that described above. One or more absorbing and/or scattering coating  
22 segments may be deposited on (or left on) the resonator fiber for suppressing undesirable  
23 delocalized optical modes. Alternatively, one or more scattering portions may be provided on  
24 the resonator fiber surface for scattering undesirable optical modes. Such scattering portions  
25 may be provided by any of the cylindrical processing methods disclosed and/or claimed herein,  
26 and may comprise one or more radially recessed segments and/or radially protruding members.  
27 Such coating portions, scattering members, and the like may be provided on any optical fiber on  
28 which an optical or structural member has been fabricated and which may support undesirable  
29 optical modes that may potentially interfere with the proper operation of the resonant optical  
30 power control device.

Figs. 9C and 9D show additional alignment members provided on or near a fiber-ring resonator segment 100. In a resonant optical power control device according to the present invention, a transmission fiber-optic waveguide is typically provided with a fiber-optic-taper segment 116 to serve as an evanescent coupling segment. To reproducibly establish and stably maintain evanescent optical coupling between the fiber-optic-taper segment and the fiber-ring resonator, a taper-positioner may be provided on the resonator fiber. In Fig. 9C, a radially-extending radially-tapered transverse flange 211 is provided on the resonator fiber adjacent to the fiber segment 100. This taper positioner may be fabricated using any of the cylindrical processing methods disclosed herein. A preferred method comprises a modification of the process illustrated in Fig. 3 for surface-masked etching of the resonator fiber. In addition to the two unmasked rings shown in Fig. 3, a very narrow line is machined through the resonator segment mask ring at a distance from the edge about equal to twice the desired etch depth (i.e., radius differential between the resonator segment and the etched adjacent portions), thereby dividing the masked resonator segment ring into a main masked ring and a secondary masked ring. The etch process is permitted to proceed (both longitudinally as well as radially) until two of the etched portions just meet (i.e., when the secondary masked ring just disappears), yielding the radially-extending radially-tapered transverse flange 211 shown in Fig. 9C. The taper-positioner serves to provide reproducible and stable positioning of the fiber-optic-taper segment 116 against the flange 211 and the resonator segment 100. A portion of the secondary masked ring may be machined away prior to etching, so that the flange 211 extends only partly around the circumference of the resonator fiber, thereby suppressing the ability of flange 211 to support undesirable optical modes.

An alternative taper positioner is illustrated in Fig. 9D, comprising a pair of longitudinally-juxtaposed radially-extending radially-tapered transverse flanges 212 positioned on outer circumference of the resonator segment 100 so that the fiber-optic-taper segment may rest on paired flanges. Any of the cylindrical processing methods disclosed herein may be employed to produce the paired flanges 212. A preferred method may comprise a two-step implementation of the surface-masked etching process of Fig. 3. After surface-masked etching to produce the fiber-ring resonator segment 100, a narrow line is machined in the mask material around the longitudinal midline of the masked fiber ring. Upon etching, the concave groove is formed between two circumferential ridges. The etch process is permitted to continue until the

1 flat tops of the ridges just disappear. A fiber-optic-taper segment may then rest securely against  
2 the paired flanges 212 for reproducibly established and stably maintained evanescent optical  
3 coupling between the fiber-optic-taper segment 116 and resonator segment 100.

4 In addition to stable mechanical engagement of the fiber-optic-taper segment and the  
5 resonator segment, flanges 211 and 212 provide other beneficial effects. It has been observed  
6 that when a fiber-optic-taper segment is brought into direct mechanical contact with the outer  
7 circumference of a fiber-ring resonator, the proximity of the fiber-optic-taper segment seems to  
8 induce coupling between undesirable, delocalized optical modes of the fiber-ring resonator  
9 and/or resonator fiber and/or higher order modes of the fiber optic taper. This manifests itself as  
10 an unacceptably large optical loss of the fiber-ring resonator (over and above the desired  
11 resonator optical losses due to evanescent coupling to the fiber-optic taper, optical modulator,  
12 second fiber-optic waveguide, or other component of the resonant optical control device). By  
13 displacing the fiber-optic-taper segment from the midline of the fiber ring resonator outer  
14 circumference (either longitudinally or radially), the undesirable coupling to these delocalized  
15 optical modes can be substantially reduced or eliminated, albeit the expense of reduced coupling  
16 strength between the fiber-optic-taper segment and the fiber-ring resonator. Flange 211 serves to  
17 position the fiber-optic taper segment 116 in a longitudinally-displaced position relative to fiber-  
18 ring resonator segment 100, while flanges 212 serve to position fiber-optic-taper segment in a  
19 radially-displaced position relative to fiber-ring resonator segment 100.

20 The mechanical stability of fiber-optic-taper segment 116 evanescently optically coupled  
21 to fiber-ring resonator segment 100 with taper positioner 211 or 212 may be further enhanced by  
22 tacking or welding the taper segment to the fiber ring resonator and/or taper positioner. A  
23 preferred method for doing so comprises "spot welding" the taper to the positioner or fiber-ring  
24 with a short burst from a CO<sub>2</sub> laser. The mechanical stability of the optical system is enhanced  
25 while typically introducing only minimal additional insertion loss into the fiber-optic-tapered  
26 waveguide.

27 In order to achieve and maintain reliable, reproducible, and stable evanescent optical  
28 coupling between a transmission optical waveguide, a circumferential-mode resonator, and an  
29 optical modulator (for a resonant optical modulator) or second optical waveguide (for a resonant  
30 optical filter) during and after manufacture of a resonant optical power control device according

1 to the present invention, an alignment device may be employed, as illustrated by the exemplary  
2 assemblies of Figs. 11-14. Such an alignment device may comprise a first alignment substrate  
3 502 having a transmission-waveguide-alignment groove 506 thereon, and various embodiments  
4 are described in detail in earlier-cited applications A4, A5, and A7. Alignment substrate 502  
5 may be further provided with a circumferential-mode-resonator-alignment groove 504, or groove  
6 504 may be provided on a second alignment substrate 702. A method for fabricating a resonant  
7 optical power control device according to the present invention comprises the steps of: 1)  
8 positioning and securing a transmission fiber-optic waveguide within the transmission-  
9 waveguide-alignment groove 506; and 2) positioning and securing the circumferential-mode  
10 optical resonator within the resonator-alignment groove 504 (as shown, for example, in 11A-11C  
11 for the case when grooves 504 and 506 are both provided on substrate 502). The transmission  
12 fiber-optic- waveguide may comprise a fiber taper 600, an optical fiber with a saddle-shaped  
13 evanescent optical coupling segment, a D-shaped optical fiber, or any other functionally  
14 equivalent transmission optical waveguide having an evanescent coupling segment. The  
15 circumferential-mode resonator may comprise a fiber-ring 602 connected to adjacent portions  
16 604, or any other functionally equivalent circumferential-mode resonator structure.  
17 Notwithstanding the exemplary combinations shown in the Figures, any suitable circumferential-  
18 mode resonator may be combined with any suitable transmission fiber-optic waveguide to yield a  
19 resonant optical power control device according to the present invention. The transmission-  
20 waveguide-alignment groove 506 may be positioned on the alignment substrate 502, and  
21 resonator-alignment groove 504 may be positioned on the alignment substrate 502 or 702, so that  
22 when positioned and secured therein (and substrates 502 and 702 are assembled, if groove 504 is  
23 provided on substrate 702), the transmission fiber-optic waveguide and the circumferential-mode  
24 resonator are in substantial tangential or circumferential engagement (preferably mechanical  
25 contact between a fiber-optic-taper segment and a taper-positioner provided for the fiber-ring  
26 resonator, as described above), thereby evanescently optically coupling the circumferential-mode  
27 resonator to the transmission fiber-optic waveguide.

28 As shown in the Figures, the resonator-alignment groove and the fiber-alignment groove  
29 may preferably be substantially perpendicular, so that the fiber and circumferential-mode  
30 resonator may be substantially co-planar. The alignment grooves may have substantially  
31 constant width and depth profiles along their respective lengths, or alternatively may have



1 tailored width and/or depth profiles. The cross-sectional shape of the alignment grooves may  
2 preferably be substantially rectangular (in fact probably slightly trapezoidal due to laser  
3 machining), but may alternatively have any suitable cross-sectional shape suitable for positioning  
4 and securing the circumferential-mode resonator and the transmission optical fiber. The depths  
5 of the resonator-alignment groove and fiber groove are preferably chosen so that when  
6 positioned and secured therein, the fiber and a fiber-taper positioner of the circumferential-mode  
7 resonator are in direct contact and therefore optically coupled in a reproducible, reliable, and  
8 stable manner. The depths chosen depend on the mechanical configurations of the  
9 circumferential-mode resonator and the transmission fiber, as may be readily determined for a  
10 particular configuration by one skilled in the art. Either the fiber-alignment groove or the  
11 resonator-alignment groove may be the deeper groove, and typically the component (fiber or  
12 resonator) corresponding to the deeper groove is positioned and secured in its respective groove  
13 first, and the other component positioned and secured after the first, although this need not  
14 always be the case. For example, if a plurality of circumferential-mode resonators are to be  
15 coupled in series to a single transmission optical fiber (a plurality of resonant optical modulators  
16 for independently modulating multiple optical signal channels, for example), it may be preferable  
17 to tangentially or circumferentially engage the transmission optical fiber alternately (by ones or  
18 twos) from opposite sides to ensure reproducible optical coupling with all of the circumferential-  
19 mode resonators. It may be desirable in this instance to provide two alignment substrates with  
20 alignment grooves on opposing faces thereof, thereby allowing access to opposing sides of a  
21 transmission optical fiber positioned within a fiber alignment groove thereof. Alternatively,  
22 alignment grooves may be provided at three or more operational depths: a deepest set of one or  
23 more resonator-alignment grooves, an intermediate fiber-alignment groove, and a shallowest set  
24 of one or more resonator-alignment grooves (Figure 15).

25 Any of a variety of functionally equivalent methods may be employed for securing the  
26 transmission optical fiber and/or the circumferential-mode resonator within the respective  
27 alignment groove, including but not limited to: application of adhesives, epoxies, resins,  
28 polymers, solders, and the like; welding or fusing; and providing a mechanical retainer for  
29 retaining the transmission fiber and/or circumferential-mode resonator within the respective  
30 alignment groove, such as a clamp, clip, fastener, plate, or other like device. In an alternative  
31 embodiment of an optical power control device, the transmission optical fiber may be fused or

1 welded (with a CO<sub>2</sub> laser, for example) to the circumference of a circumferential-mode resonator  
2 to insure stable, reliable, and reproducible optical coupling. Once the transmission optical fiber  
3 and circumferential-mode resonator have each been positioned and secured within the respective  
4 alignment groove, the alignment device may be sealed (preferably hermetically sealed) to isolate  
5 the fiber and resonator from the use environment of the optical power control device. This is  
6 important for a number of reasons. First, the optical coupling relies on the propagation of  
7 evanescent optical waves from free surfaces of the transmission fiber and circumferential-mode  
8 resonator. Any contamination of these free surfaces may drastically alter the optical properties  
9 of the fiber and/or resonator and/or optical coupling thereof, thereby altering the performance of  
10 the optical power control device. Similarly, any movement of the transmission optical fiber  
11 relative to the circumferential-mode resonator may also alter the optical coupling and  
12 performance of the control device. The alignment device may comprise a cover, second  
13 substrate, or other functionally equivalent component that may be positioned over the alignment  
14 grooves and sealed into place (using adhesives, epoxies, resins, polymers, solders, and/or the  
15 like; or using welding or fusion), leaving the two ends of the transmission optical fiber exposed  
16 for connecting to an optical power transmission system.

17 In a preferred embodiment of an optical power control device according to the present  
18 invention, a circumferential-mode fiber-ring resonator is employed having been fabricated from  
19 an optical fiber as disclosed hereinabove. A fiber-ring resonator may be particularly well-suited  
20 for use in the optical power control device fabrication methods described herein. The adjacent  
21 portions may serve to reproducibly, reliably, and stably position the fiber-ring resonator segment  
22 within the resonator-alignment groove, particularly in directions substantially orthogonal to the  
23 longitudinal axis of the resonator segment and adjacent portions. Proper longitudinal positioning  
24 is required so that the transmission optical fiber 600 engages the resonator segment 100 and not  
25 an adjacent portion 200. This may be most simply accomplished by providing a blind resonator-  
26 alignment groove 504, truncating an adjacent portion 200 at an appropriate length, and  
27 positioning the circumferential-mode resonator 100 in resonator-alignment groove 504 so that  
28 the truncated end of adjacent portion 200 butts up against the blind end of resonator-alignment  
29 groove 504. If the truncated end is angle polished and the blind groove end is angled, rotation of  
30 the fiber may serve to adjust the lateral position of the circumferential-mode resonator.  
31 Alternatively, alignment structures provided on the adjacent portions may serve to properly

1 longitudinally position the circumferential-mode resonator within the resonator-alignment  
2 groove (Figs. 9A and 9B). Preferred alignment structures that may be provided on one or more  
3 of the adjacent portions 200 may comprise circumferential grooves 220 and/or circumferential  
4 annular flanges 210 for engaging corresponding alignment members (flanges 520 and/or grooves  
5 510, respectively) that may be provided in the resonator-alignment groove 504 of the alignment  
6 device 500 (Fig. 16). Details of fabrication of a circumferential-mode resonator having such  
7 alignment members are disclosed hereinabove. Other suitable alignment members may be  
8 employed while remaining within the scope of inventive concepts disclosed and/or claimed  
9 herein.

10 A major portion of the cost associated with manufacture of optical power control devices  
11 arises from the labor-intensive steps involved in properly aligning the components of the device.  
12 Often active alignment techniques are required wherein some measure of device performance  
13 (examples include insertion loss, modulation depth, bandwidth, and so forth) is monitored and  
14 optimized with respect to alignment of components of the device. Such active alignment steps  
15 are reduced or substantially eliminated from fabrication of a resonant optical power control  
16 device according to the present invention. In particular, appropriate depths chosen for the  
17 resonator-alignment groove and the fiber-alignment groove, and circumferential grooves and/or  
18 annular flanges provided on an adjacent portion and appropriately positioned mating structures in  
19 the resonator-alignment groove for engaging the adjacent portion, both serve to enable  
20 positioning the circumferential-mode resonator segment in substantial engagement with the  
21 transmission fiber when each is positioned within the respective alignment groove, without any  
22 need for active monitoring of device properties during assembly and/or alignment. Such passive  
23 alignment techniques substantially reduce manufacturing time and cost, and substantially  
24 enhance reliability and consistency of the manufactured devices.

25 The transmission optical fiber 600 may preferably be provided with a fiber-optic-taper  
26 segment 604. Such a taper may be provided, for example, in a single-mode optical fiber by  
27 heating a segment of the fiber while pulling on the ends of the fiber. For a typical single-mode  
28 fiber having an outer diameter (core plus cladding) of about 125  $\mu\text{m}$ , for example, this procedure  
29 results in a smoothly varying fiber diameter which decreases from about 125  $\mu\text{m}$  to between  
30 about 1  $\mu\text{m}$  to about 10  $\mu\text{m}$  and then increases to about 125  $\mu\text{m}$ , over a taper length of at least a  
31 few hundred microns ranging up to several millimeters of even centimeters. Taper segments

1 between about 2  $\mu\text{m}$  and about 4  $\mu\text{m}$  in diameter over a taper length of about a millimeter or two  
2 are preferred, and may be obtained by heating and pulling a reduced-diameter fiber (described  
3 further below). The smooth variation in fiber diameter permits virtually lossless transmission of  
4 a traveling optical wave along the fiber. However, the optical wave comprises a significant  
5 evanescent portion extending radially beyond the circumference of the narrow part of the taper.  
6 Upon assembly of an optical power control device according to the present invention, the fiber  
7 taper segment of the transmission optical fiber and the circumferential-mode resonator segment  
8 may each be positioned and secured in respective alignment grooves so that the resonator  
9 segment is in substantial tangential or circumferential engagement (in mechanical contact with a  
10 fiber-taper positioner, for example) with the fiber taper segment. As described earlier herein,  
11 appropriate depths of the alignment grooves and mating alignment structures on the adjacent  
12 portions and resonator-alignment groove may be employed to enable reproducible, reliable, and  
13 stable optical coupling of the circumferential-mode and the fiber taper segment without resorting  
14 to complicated and/or labor-intensive active alignment procedures.

15 The fiber taper segment described hereinabove may often prove to be quite fragile, and  
16 may be subject to frequent breakage during assembly of an optical power control device  
17 according to the present invention. Therefore, in an alternative fabrication method according to  
18 the present invention (illustrated in Figure 17), a non-tapered transmission optical fiber 600 may  
19 be positioned in the fiber-alignment groove 506. After such positioning, the transmission fiber  
20 600 may then be heated (by a flame or CO<sub>2</sub> laser at the point where it crosses the eventual  
21 position of the circumferential-mode resonator) and pulled, thereby yielding a fiber taper  
22 segment 604. The fiber taper segment 604 is thereby already positioned within the fiber-  
23 alignment groove 506 without being subjected to breakage. The transmission optical fiber (and  
24 fiber taper segment thereof) may subsequently be secured within the fiber-alignment groove. In  
25 order to facilitate this *in situ* heating and pulling of the transmission fiber to generate a fiber  
26 taper segment, the fiber-alignment groove 506 may preferably be provided with an enlarged  
27 central portion 510, deeper and/or wider than the remaining end portions of the fiber-alignment  
28 groove 506. The enlarged portion of the fiber-alignment groove preferably corresponds to the  
29 eventual location of the fiber taper segment 604 and resonator segment 100, and reduces or  
30 substantially eliminates mechanical and/or thermal contact between the alignment substrate 502  
31 and the portion of the transmission optical fiber 600 that is heated and pulled to form the fiber

1 taper segment 604. In this way, thermal and/or mechanical disturbances that may distort and/or  
2 degrade the fiber taper segment during heating and pulling may be reduced and/or substantially  
3 eliminated, thereby enabling reliable and reproducible production of the fiber taper segment. It  
4 may be desirable for the enlarged portion 510 of the groove 506 to extend through the alignment  
5 substrate 502 so that the flame or CO<sub>2</sub> laser used to heat the fiber does not also heat and/or  
6 damage the alignment substrate 502.

7 Fiber tapers may be pulled from standard single-mode optical fiber or polarization  
8 preserving optical fiber ("panda", elliptical core, or other) which typically has a cladding outer  
9 diameter of about 125  $\mu\text{m}$  and a core diameter of between about 5  $\mu\text{m}$  and about 10  $\mu\text{m}$ . When  
10 heated and pulled to yield a fiber taper having the desired diameter (between about 1 and about  
11 10  $\mu\text{m}$ , preferably between about 2  $\mu\text{m}$  and about 4  $\mu\text{m}$ ), the length of the taper section may  
12 typically reach about 10 to 20 mm in length, necessitating a relatively long fiber-alignment  
13 groove, and relatively large alignment substrate and alignment device. This relatively long fiber  
14 taper segment may also reduce the stability of the optical power control device, since the  
15 relatively long fiber taper segment may move within the enlarged portion of the fiber-alignment  
16 groove thereby changing the degree of optical coupling between the fiber taper segment and the  
17 circumferential-mode resonator. This problem may be mitigated, and the overall sizes of the  
18 fiber-alignment groove and alignment substrate reduced, by pre-thinning the transmission optical  
19 fiber before heating and pulling to produce a fiber taper segment. A 125  $\mu\text{m}$  fiber may be pre-  
20 thinned by etching or heating/pulling to a diameter of about 50  $\mu\text{m}$ . This fiber thickness is still  
21 sufficiently robust to withstand positioning with a fiber-alignment groove. Heating and pulling  
22 the pre-thinned fiber to a diameter of 2-3  $\mu\text{m}$  may also be performed *in situ* without the need for  
23 an enlarged portion of the fiber-alignment groove and yielding a shorter and therefore more  
24 mechanically stable fiber taper segment. Additionally it is found that pre-etching provides a  
25 more robust means of achieving a low insertion loss taper.

26 The embodiment of Fig. 15 suggests a method for even more reproducible and stable  
27 evanescent optical coupling between a fiber-optic-taper segment and a fiber-ring optical  
28 resonator. By wrapping the fiber-optic-taper segment partially around the fiber-ring resonator,  
29 an extended region for evanescent optical coupling is created. Furthermore, the level of  
30 evanescent optical coupling is adjustable, since the degree of coupling is directly related to the  
31 interaction length. When used in conjunction with the fiber-taper positioners described

hereinabove, wrapping the taper around the fiber-ring optical resonator enables essentially full adjustment of the coupling condition of the fiber-optic taper and the fiber-ring resonator, from an under-coupled condition at first tangential contact, through critical coupling, to an over-coupled condition. In the absence of additional optical loss due to a modulator or other component, a preferred degree of coupling results in about 90% transmission through the taper on resonance, yielding linewidths commensurate with typical WDM or DWDM systems. The taper may be wrapped around the fiber-ring resonator to any desired degree, but wrapping angles between about  $0^\circ$  and about  $180^\circ$  are typical, and angles between about  $45^\circ$  and about  $180^\circ$  are preferred. Generally, an interaction length on the order of  $50\text{ }\mu\text{m}$  to about  $150\text{ }\mu\text{m}$  result in a degree of coupling in the desired range.

In the embodiment of Fig. 18, a single fiber-taper is shown following a serpentine path through a series of vertically displaced fiber-rings. The depths of the grooves, fiber ring diameters, and distance between the fiber-rings determines the angular range of the wrapping (or equivalently, the interaction length for evanescent optical coupling). Once the desired degree of wrapping is determined (through some experimentation), the appropriate dimensions can be used to fabricate an alignment substrate for producing the desired wrapping. Each of the fiber rings of Fig. 18 may be a fiber-ring resonator, and may function as a component of an optical power control device (modulator, filter, or other). Alternatively, some of the rings (and perhaps all save one) may be provided strictly for providing a reproducible and stable degree of evanescent optical coupling by taper wrapping. One or more of the fiber-rings of Fig. 18 may in fact comprise a pair of tapered flanges, similar to flanges 212 of Fig. 9D. These paired flanges may therefore provide for supported wrapping of a fiber-optic taper with minimal optical interference. The fiber on which the paired flanges are fabricated may be provided with delocalized-optical-mode suppressors for that very reason. The fiber-optic taper may also be welded to one or more of the fiber-rings of Fig. 18. Instead of using fiber rings as taper-wrapping support members in the way, such members may alternatively be incorporated onto the alignment substrate. It is also found that supported wrapping may be used to confine the bent sections of the taper to those sections in which the optical mode is guided by the dielectric/air interface which is essential to reduce bending induced mode coupling effects.

For a resonant optical modulator, the second alignment substrate 702 of the alignment device may have an optical modulator secured thereto or mounted thereon for a resonant optical

1 modulator, as in Figs. 12-14. Alternatively, the second transmission optical waveguide may be  
2 provided for a resonant optical filter, as in Figs. 19-21, either on the first alignment substrate (Fig.  
3 20) or on the second alignment substrate (Figs. 19 and 21). Alignment substrate 702 (and/or  
4 alignment substrate 502, if groove 504 is provided thereon) may be suitably mechanically  
5 indexed or otherwise provided with means for reliably, reproducibly, and stably positioning the  
6 optical modulator for evanescent optical coupling to the circumferential-mode optical resonator  
7 (either in direct mechanical contact or a space therebetween). The alignment grooves 504 and  
8 506, and any indexing or other alignment means, together serve to suitably position the optical  
9 modulator, circumferential-mode resonator, and transmission fiber-optic waveguide relative to  
10 each other, when all are secured to the assembled alignment device.

11 For a resonant optical modulator, similar alignment substrates may be employed whether  
12 the optical modulator is a waveguide or resonator, and whether the optical modulator is loss-  
13 modulated, index-modulated, resonance-modulated, or interference-modulated. Exemplary  
14 assemblies include: slab modulator waveguide 132 shown in Figs. 12A-12B (with groove 504 on  
15 substrate 502); 2D modulator waveguide 134 on substrate 136 shown in Figs. 13A-13B (with  
16 groove 504 on substrate 502); and ridge modulator waveguide 2252 shown in Figs. 14A-14B  
17 (with groove 504 on substrate 702).

18 For each of the various modulator structures, methods, and materials recited hereinabove  
19 for a circumferential-mode resonator, some sort of control signal must be applied to the  
20 modulator. A modulator controller may therefore be provided on the alignment device for  
21 providing such signals to a modulator of a circumferential-mode resonator. Such signals may  
22 comprise an electronic control signal, an optical control signal, a mechanical control signal,  
23 and/or other control signal, and the modulator controller may comprise means for applying such  
24 control signals to the modulator. Examples of such means may include, but are not limited to:  
25 electrical conductors, wires, cables, electrodes, electrical contacts, ohmic contacts, wireless  
26 transmitters and/or receivers, semiconductors, semiconductor hetero-structures (including  
27 quantum wells), diodes, triodes, transistors, field-effect transistors (FET's), CMOS devices,  
28 integrated circuits, ASIC's, digital circuits, analog circuits, optical fibers, lenses, micro-lenses,  
29 mirrors, prisms, integrated optics, adaptive optics, light sources, laser sources, laser diodes, light-  
30 emitting diodes (LED's), photo-voltaic devices, photo-conductive devices, piezo-electric  
31 devices, electro-strictive devices, actuators, translators, rotators, linear and/or rotary stepper

1 motors, linear and/or rotary servo systems, combinations thereof, and/or functional equivalents  
2 thereof. A portion of the modulator controller may reside on and/or within the alignment  
3 device, and access to the modulator controller may be provided enabling control of the  
4 modulator after hermetic sealing of the alignment device. Such access may comprise feed-  
5 through connectors, access ports, embedded conductors and/or optical fibers, and the like for  
6 transmitting optical, electronic, or mechanical control signals.

7 In a resonant optical filter, the second transmission optical waveguide (preferably a fiber-  
8 optic waveguide with a fiber-optic taper segment) is positioned in a groove on the alignment  
9 substrate, either the first alignment substrate (Fig. 20) or the second alignment substrate (Figs. 19  
10 and 21). Such a second alignment substrate may be suitably indexed or provided with mating  
11 alignment structure(s) to enable reproducible, reliable, and stable alignment of the second optical  
12 waveguide with the circumferential-mode resonator when the optical power control device is  
13 assembled. The alignment device, including the first transmission optical fiber, the  
14 circumferential-mode optical resonator, and the second transmission optical fiber, may be sealed  
15 (preferably hermetically sealed) after assembly, as disclosed hereinabove. A cover, the second  
16 alignment substrate, or another functionally equivalent component may be positioned over the  
17 alignment grooves and sealed into place (using welding, fusion, adhesives, epoxies, resins,  
18 polymers, solders, and/or the like), leaving only the two ends of the transmission optical fibers  
19 exposed for connecting to an optical power transmission system.

20 The alignment device, comprising one or more grooved and/or indexed alignment  
21 substrates, may be fabricated from a material sufficiently rigid to provide reliable, reproducible,  
22 and stable positioning of the transmission optical fiber, circumferential-mode resonator, and any  
23 secondary or modulator optical assembly that comprise the optical power control device.  
24 Preferred materials may include ceramics or semiconductors such as silicon or a III-V  
25 semiconductor, but other material (such as metals, alloys, glasses, crystalline materials, and  
26 dielectric materials) may be employed while remaining within the scope of inventive concepts  
27 disclosed and/or claimed herein. The fiber-alignment groove and the resonator-alignment groove  
28 may be formed by any suitable means for machining (or otherwise processing) the material used.  
29 A preferred method for providing the grooves is laser machining (most preferably ablative laser  
30 machining with an excimer laser), however, other fabrication techniques may be employed, such  
31 as lithographic patterning of a mask followed by wet (chemical) or dry (reactive ion) etching,



1 electric discharge machining, plasma discharge machining, or single wire arc ablation. These  
2 same machining/processing techniques may be employed for providing other alignment and/or  
3 indexing structures on the alignment device (such as tabs, slots, pins, holes, grooves, and the  
4 like).

5 A resonant optical filter according to the present invention is shown schematically in  
6 Figs. 19-21, in which circumferential-mode optical resonator 100 is evanescently optically  
7 coupled to transmission optical waveguides 600 and 750. An optical signal propagating in  
8 waveguide 600 and substantially resonant with resonator 100 will be at least partially transferred  
9 or routed to waveguide 750. The resonant optical filter may function as a channel dropping filter  
10 if only one signal channel transmitted into waveguide 600 is resonant with resonator 100 and  
11 therefore routed to waveguide 750. If the evanescent optical coupling between waveguide 600  
12 and resonator 100 is substantially equal to the evanescent optical coupling between waveguide  
13 750 and resonator 100, then (neglecting internal resonator optical loss, which can be made small)  
14 the resonant optical channel is substantially completely dropped from waveguide 600 and  
15 substantially completely transferred to waveguide 750. Similarly, the resonant optical filter may  
16 be used as a channel adding filter if a resonant optical signal enters waveguide 750 and is  
17 transferred to waveguide 600. If the evanescent optical coupling is not the same for both  
18 waveguides, then the optical signal transfer is incomplete, resulting in division of a resonant  
19 optical signal entering the filter.

20 If multiple optical signal channels are resonant with resonator 100, then the resonant  
21 optical filter may function as an optical slicer and/or optical interleaver, for dividing/combining,  
22 respectively, a plurality of optical signals at different wavelengths. The spectral characteristics  
23 of the resonances of resonator 100 determine the operational characteristics of the resonant  
24 optical filter. If resonator 100 is a single resonator with fairly spectrally narrow resonance peaks,  
25 then the resonant optical filter will have correspondingly narrow "transfer peaks" or "routing  
26 peaks". The resonance characteristics of the resonant optical filter may be manipulated by  
27 optically coupling multiple optical resonators. A system of four coupled resonators is shown in  
28 Fig. 20, for example. Figs. 22A and 22B show the resonance spectra of systems of coupled,  
29 substantially identical optical resonators. A single resonator is shown exhibiting a single  
30 resonant mode. Two coupled resonators exhibit two resonant modes with differing frequencies  
31 (corresponding to symmetric and anti-symmetric linear combinations of the isolated resonator

1 modes, or “supermodes”). In general  $N$  coupled resonators will possess  $N$  supermodes; the  $N$   
2 supermodes are distributed within a frequency band  $V$  set by the strength of the inter-ring optical  
3 coupling. When  $V/N$  is on the order of the resonance linewidth of the individual rings, the  
4 supermode resonances are unresolvable and the resulting filter function approximates a square  
5 top function. This square top function is useful for a resonant optical filter since it reduces the  
6 need to precisely match the filter resonance to the signal channel wavelength. In WDM and  
7 DWDM systems, a given signal channel is generally specified to lie within a specified band of  
8 frequencies. Using a multiple coupled resonators enables the “routing band” of the resonant  
9 optical filter to substantially encompass the band of frequencies of an optical signal channel,  
10 facilitating the use of the resonant optical filter.

11 The spectral spacing between adjacent resonance peaks or resonance bands may be  
12 manipulated to produce a resonant optical filter with particular wavelength dependent routing  
13 characteristics, for either single- or multiple-resonator devices. A particularly useful device in  
14 WDM and DWDM systems are slicer/interleavers wherein every other optical signal channel is  
15 routed from one waveguide to the other. A preferred filter function for such a device would  
16 comprise a series of routing bands separated (“center-to-center”) by twice the channel  
17 wavelength spacing of the WDM or DWDM system and about equal to the channel spacing in  
18 width (such channel spacings may range from more than several hundred GHz down to tens of  
19 GHz, depending on the particular system). Other slicer/interleaver devices may be constructed  
20 wherein the routing peak/band spacing and width are chosen to route other combinations of  
21 optical signal channels. For example, the resonance spacing may preferably be chosen to be an  
22 integer multiple  $N$  of the channel spacing, while the resonance width might be chosen to be an  
23 integer multiple  $M$  of the channel spacing, with  $M < N$ . The resulting filter function would route  
24  $M$  consecutive channels out of each successive group of  $N$  channels. Other filtering schemes  
25 may be implemented without departing from inventive concepts disclosed and/or claimed herein.

26 Any circumferential-mode optical resonator disclosed herein may be employed in a  
27 resonant optical filter according to the present invention. A coupled multiple resonator system  
28 may comprise any suitable grouping of coupled optical resonators which includes at least one  
29 circumferential optical mode as disclosed herein while remaining within the scope of the present  
30 invention. A preferred embodiment is shown in Fig. 20, wherein four fiber-ring optical  
31 resonators are shown on a common resonator fiber, the fiber-ring resonators being longitudinally

1 evanescently optically coupled. Fabrication of substantially identical fiber-rings substantially  
2 uniformly spaced results in reasonably predictable resonant optical filter functions. A multiple  
3 coupled optical resonator system may alternatively include two or more fiber-ring resonators on  
4 different fibers and radially evanescently optically coupled, as shown in Fig. 21.

5 As described above, a resonant optical filter functions as an essentially passive device.  
6 Active resonant optical filters may be implemented according to the present invention by adding  
7 an optical modulator and modulator controller to a fiber-ring resonator of the resonant optical  
8 filter. Any of the loss-, absorption-, or coupling-modulated schemes disclosed herein may be  
9 employed as in the case of resonant optical modulators, with the second optical waveguide  
10 taking the place of the optical modulator of the resonant modulator. By spoiling the resonance of  
11 the fiber-ring resonator by increasing resonator optical loss, for example, the routing function  
12 can be "turned off" for the resonant signal channels. Any of the modulation techniques disclosed  
13 herein may be adapted for producing active resonant optical filters according to the present  
14 invention.

15 Once coupled into the circumferential-mode optical resonator, dissipation of the optical  
16 signal may be modulated to in turn modulate the level of transmission of the propagating optical  
17 mode through the fiber-optic waveguide (and hence through the optical power control device), as  
18 described in the earlier-cited patent applications A1 through A6. By controllably adjusting the  
19 loss per round trip experienced by the circumferential optical mode circulating within the  
20 circumferential-mode optical resonator, the optical power control device may function in either  
21 of two modes:

22 1) Switching the circumferential-mode optical resonator between an over-coupled  
23 condition (where the loss per round trip in the circumferential-mode optical resonator is small  
24 compared to the optical coupling between the fiber-optic waveguide and circumferential-mode  
25 optical resonator, and the transmission through the fiber-optic waveguide past the resonator is  
26 large) and the condition of critical coupling (at which the optical coupling of the fiber-optic  
27 waveguide and circumferential-mode optical resonator is substantially equal to the round trip  
28 loss of the circumferential-mode optical resonator, and substantially all of the optical power is  
29 dissipated by/from the circumferential-mode optical resonator resulting in near zero optical

1 transmission through the fiber-optic waveguide past the circumferential-mode optical resonator);  
2 or

3 2) Switching states between the condition of critical coupling (near zero transmission  
4 through the fiber-optic waveguide) and a condition of under-coupling (where the loss per round  
5 trip in the circumferential-mode optical resonator is large compared to the optical coupling  
6 between the fiber-optic waveguide and circumferential-mode optical resonator, and the  
7 transmission through the fiber-optic waveguide past the circumferential-mode optical resonator  
8 is non-zero).

9 For all of these modes of operation, there are essentially two classes of mechanism by  
10 which one can introduce round trip loss to a circulating optical wave (i.e., resonant  
11 circumferential optical mode) in the circumferential-mode resonator. Either optical power of the  
12 circulating wave can be absorbed, or it can be gated out of the circumferential-mode optical  
13 resonator into a second optical element, such as a second waveguide or second resonator. The  
14 gating may preferably be achieved by control of the optical coupling between the  
15 circumferential-mode optical resonator and the second optical element and functions rather like a  
16 trapdoor. These two general possibilities are both disclosed in earlier-cited applications A1, A2,  
17 A5, and A6. The current disclosure describes such devices in greater detail, particularly optical  
18 loss transducers or elements provided as a separate element to control optical loss from a  
19 circumferential-mode resonator by either of these means (as distinguished from designs in which  
20 the loss control element is an integral part of the circumferential-mode optical resonator  
21 structure).

22 The modulator may be provided in a variety of ways, including but not limited to: in a  
23 circumferential-mode resonator fabricated by providing material on the circumference of a  
24 resonator fiber segment, the material provided may enable modification of optical properties of  
25 the circumferential-mode resonator; in a circumferential-mode resonator fabricated by spatially-  
26 selective doping of a resonator fiber segment, the doped material may enable modification of  
27 optical properties of the circumferential-mode resonator; a modulator material may be provided  
28 on at least a portion of the circumference of the circumferential-mode resonator and therefore be  
29 encompassed by an evanescent portion of the circumferential-mode optical wave extending  
30 radially from the resonator fiber segment; an adjacent fiber segment may be truncated

1 sufficiently close to the resonator fiber segment so that at least a portion of the resulting fiber end  
2 face is encompassed by a evanescent wave portion of the circumferential-mode optical wave  
3 extending longitudinally from the resonator fiber segment, and a modulator material may be  
4 provided on the portion of the fiber end face thus encompassed; combinations thereof; and/or  
5 functional equivalents thereof. The modulator material (including deposited, bonded, attached,  
6 and/or doped material) may include but is not limited to: an electro-optic material; an electro-  
7 absorptive material; a non-linear optical material; a semi-conductor material (including hetero-  
8 structures such as quantum wells); an optical gain medium (a laser material, for example); a  
9 piezo-electric material; combinations thereof; and/or functional equivalents thereof. The  
10 modulator may enable controlled modulation of one or more optical properties of the  
11 circumferential-mode resonator, including but not limited to: optical gain and/or loss; optical  
12 coupling to the circumferential-mode resonator; a resonant frequency of the circumferential-  
13 mode resonator; combinations thereof; and/or functional equivalents thereof. For each of the  
14 various modulator structures, methods, and materials recited hereinabove for a circumferential-  
15 mode resonator, some sort of control signal must be applied to the modulator. A modulator  
16 control element may therefore be provided on the alignment device for providing such signals to  
17 a modulator of a circumferential-mode resonator. Such signals may comprise an electronic  
18 control signal, an optical control signal, a mechanical control signal, and/or other control signal,  
19 and the modulator control element may comprise means for applying such control signals to the  
20 modulator.

21 The application of a control signal to a modulator of a circumferential-mode resonator via  
22 a modulator control element enables controlled modulation of the optical power transmitted  
23 through the transmission optical fiber of the optical power control device. This may be  
24 accomplished in a variety of ways, depending on the nature of the modulator employed, and  
25 several specific examples follow. Modulating the optical loss of the circumferential-mode  
26 resonator between essentially zero loss and the so-called critical-coupling loss (wherein the  
27 circumferential-mode resonator loss roughly equals the coupling between the transmission fiber  
28 and the circumferential-mode resonator) enables modulation of an optical wave that is resonant  
29 with a whispering-gallery mode of the circumferential-mode resonator between about 0%  
30 (substantially unattenuated transmission) and about 100% (substantially blocked transmission).  
31 A similar result may be obtained by keeping the circumferential-mode optical loss constant while

1 modulating the optical coupling between the transmission optical fiber and the circumferential-  
2 mode resonator. Alternatively, modulating a resonant frequency of a circumferential-mode  
3 having optical loss substantially equal to the critical-coupling loss may enable similar  
4 modulation of an optical wave as the circumferential-mode resonant frequency is moved out of  
5 and brought into resonance with the optical wave. The foregoing are exemplary only, and many  
6 other transmission optical fiber modulation schemes may be devised by suitable modulation of  
7 circumferential-mode resonator optical properties while remaining within the scope of inventive  
8 concepts disclosed and/or claimed herein.

9 The present invention has been set forth in the forms of its preferred and alternative  
10 embodiments. It is nevertheless intended that modifications to the disclosed resonant optical  
11 power control devices, components thereof, and methods of fabrication and use thereof may be  
12 made without departing from inventive concepts disclosed and/or claimed herein.